The Exploration of Hot and Cold Nuclear Matter

Status and Future

Berndt Mueller

CNMS @ CCNU
16 August 2013

See also: Barbara V. Jacak and B.M.
The Exploration of Hot Nuclear Matter
Science **337**, 310-314 (20 July 2012)

Duke QCD Theory

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. Department of Energy

Prologue

Impossible things

Alice laughed.
"There's no use of trying," she said.
"One can't believe in impossible things."
"I dare say you haven't had much practice,"
said the Queen. "When I was your age,
I always did it for half-an-hour a day.
Why, sometimes I believed as many as
six impossible things before breakfast!"

Through the Looking Glass
and what Alice Found There
by Lewis Carroll

Impossible things ?

When you heat up a liquid it can become a gas, but can a gas turn into a liquid when you heat it up?

Yes: Hadron gas becomes a QGP liquid when heated above T_C.

Can empty space itself be the most “perfect” fluid?

Yes: The empty space at the event horizon of a black hole.

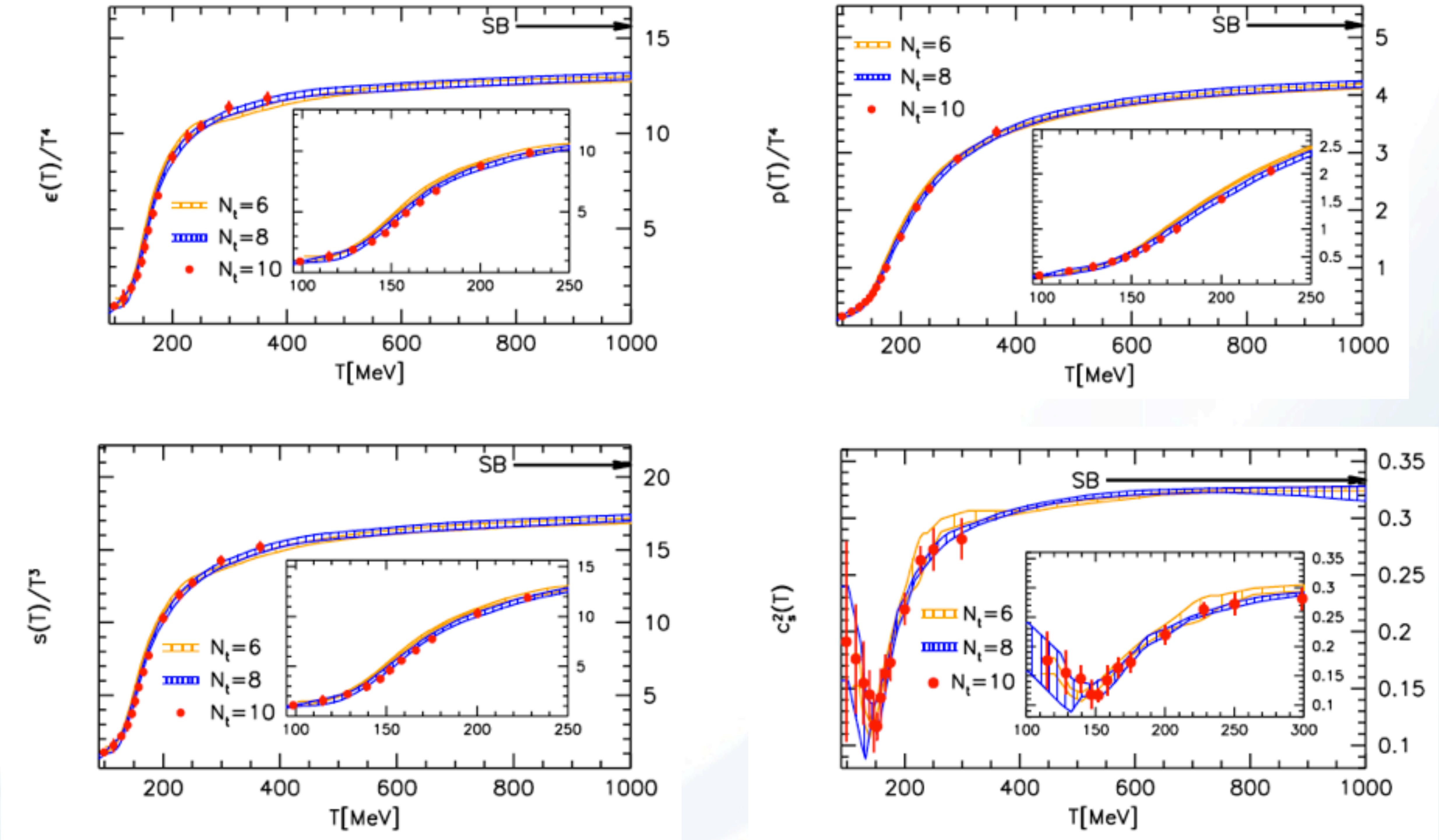
Can a Pb nucleus look just like a proton?

Yes: At small x both are a color glass condensate ($Q_S \sim (A/x)^{1/6}$).

So go and practice 1/2 hour each morning!

Introduction

QCD EOS at $\mu_B = 0$

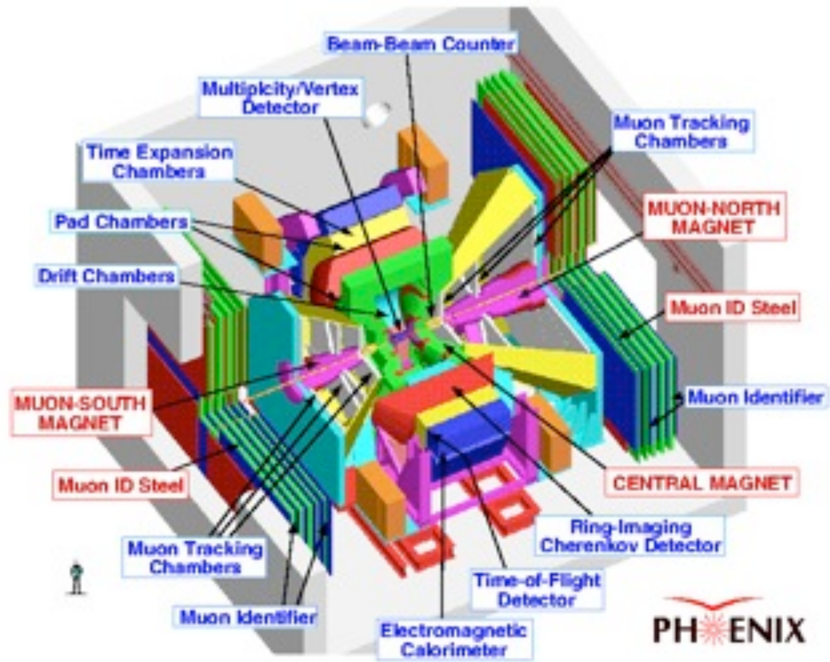


Accelerators

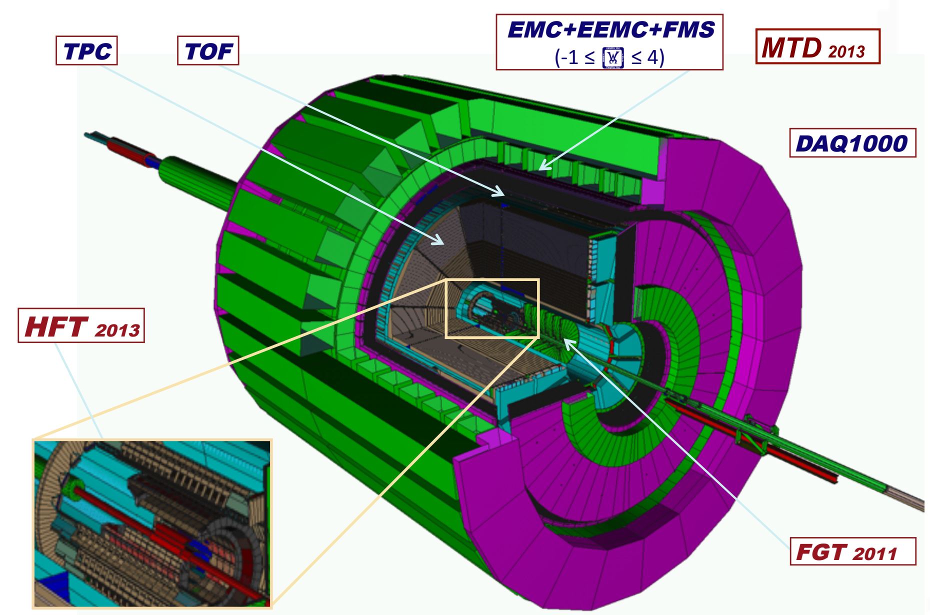
The Large Hadron Collider
27 km circumference
Energy: E_{cm} = 2.76 TeV/NN

The Relativistic Heavy Ion Collider
3.8 km circumference
Top energy: E_{cm} = 200 GeV/NN

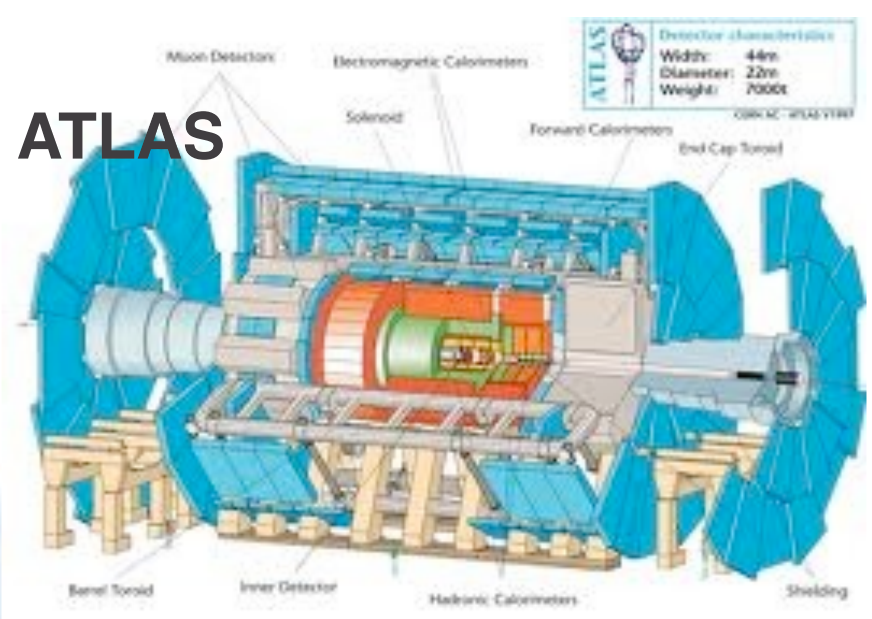
Detectors

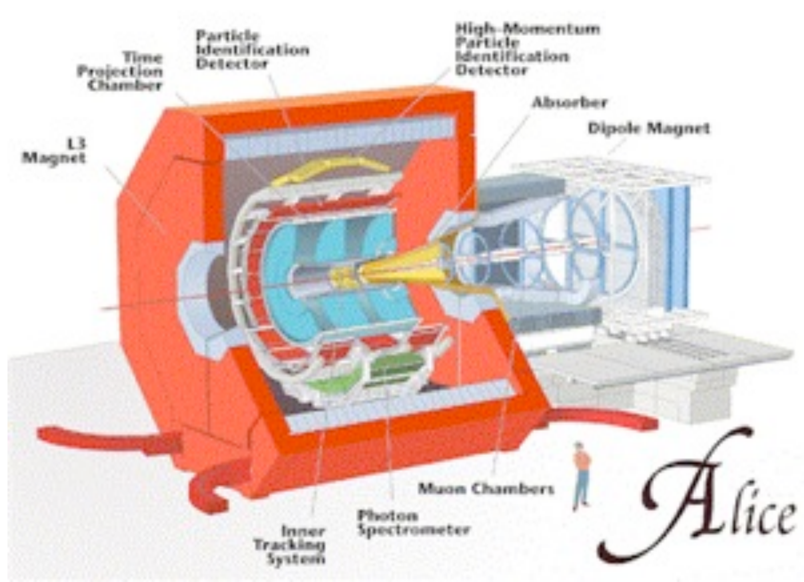


STAR Detector

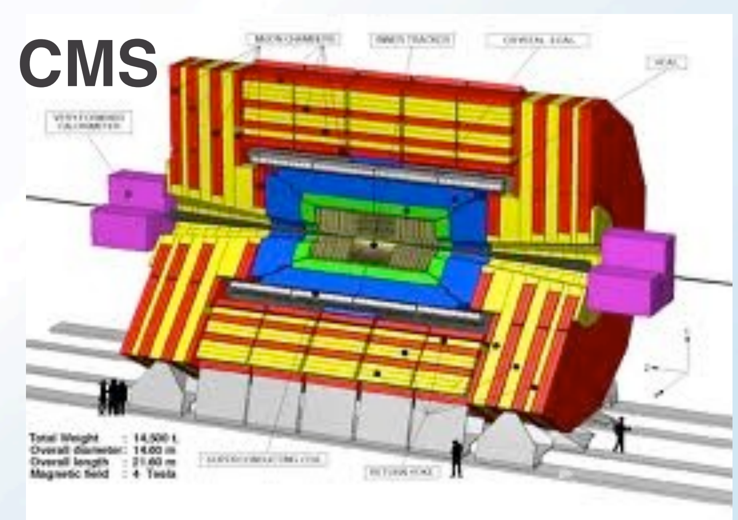


ATLAS

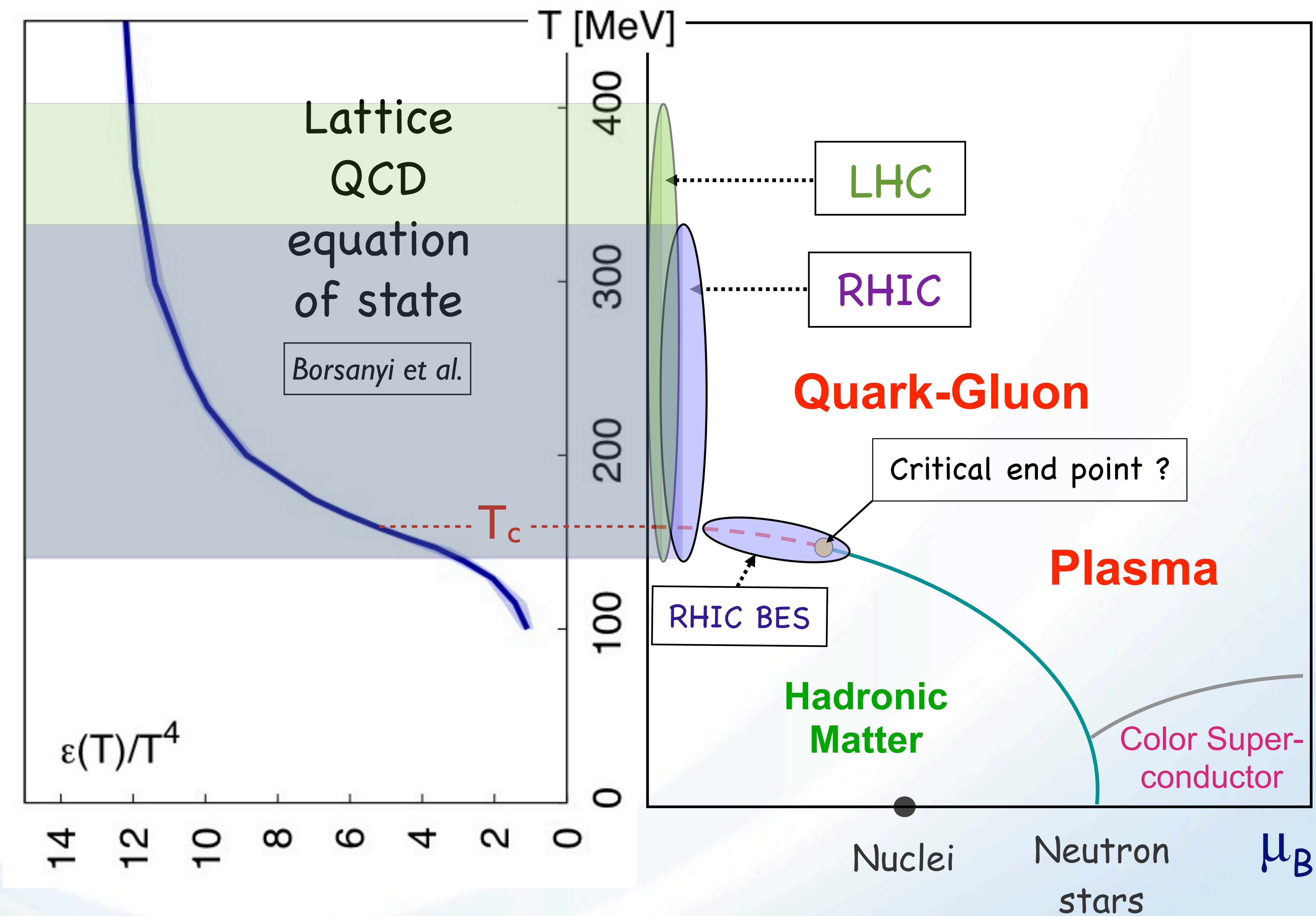




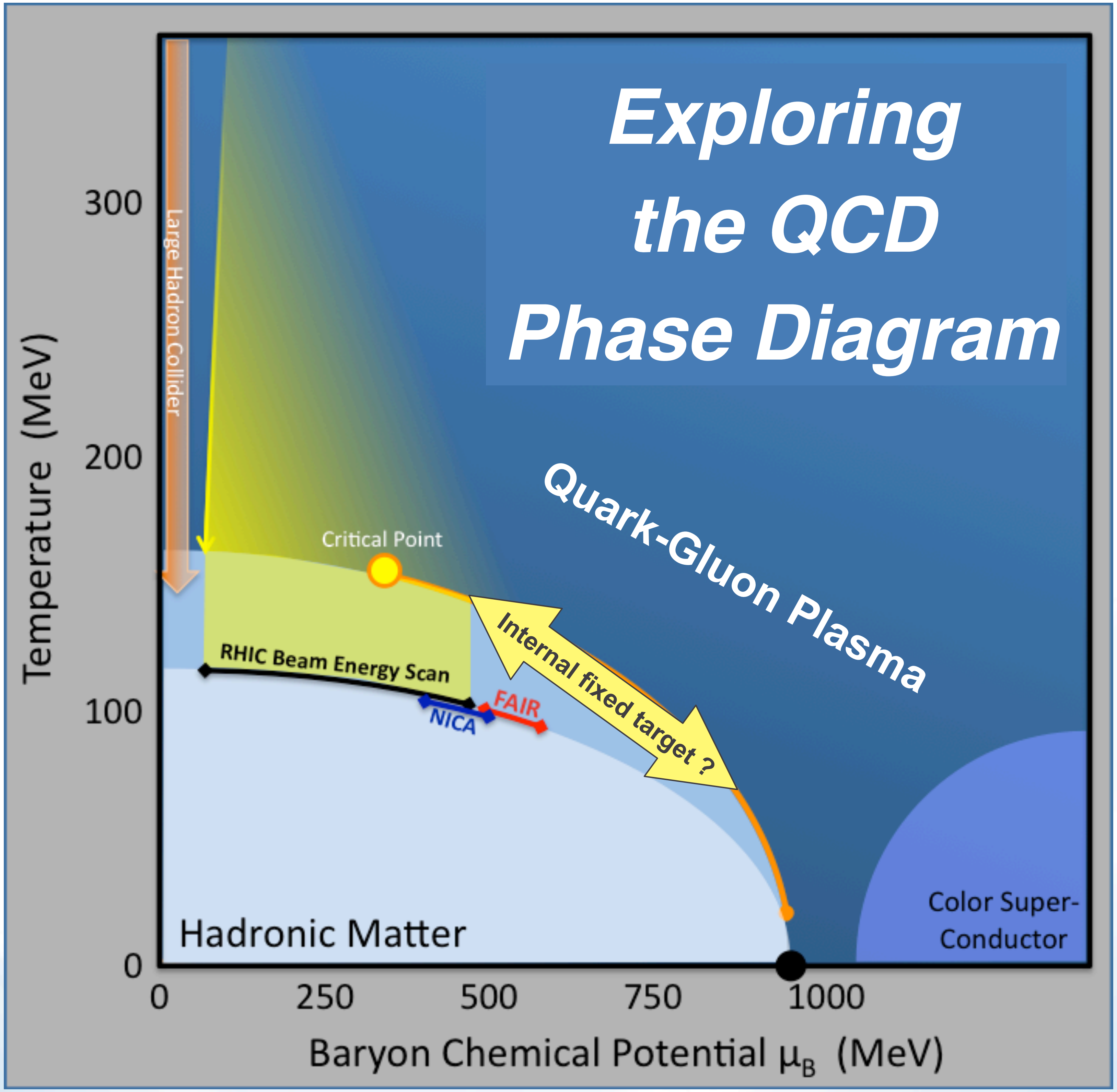
CMS



QCD Phase Diagram



Exploring the Phases of QCD Matter



RHIC is the perfect facility to explore the phases of nuclear (QCD) matter.

Covering the whole yellow shaded region requires a luminosity upgrade of RHIC to electron cooling.

Planned for 2017 with the beam energy scan II runs in 2018/19.

Results from BES I are intriguing.

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, coll. flow, fluctuations

$c_S^2 = \partial p / \partial \varepsilon$ **Speed of sound**: correlations

$\eta = \frac{1}{T}\int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$ **Shear viscosity**: anisotropic collective flow

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0)\right\rangle \\
\hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle iU^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0)\right\rangle \\
\kappa &= \frac{4\pi\alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b\right\rangle
\end{aligned}\right\}$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln\left\langle U^\dagger E^a(x) U E^a(0)\right\rangle$ **Color screening**: Quarkonium states

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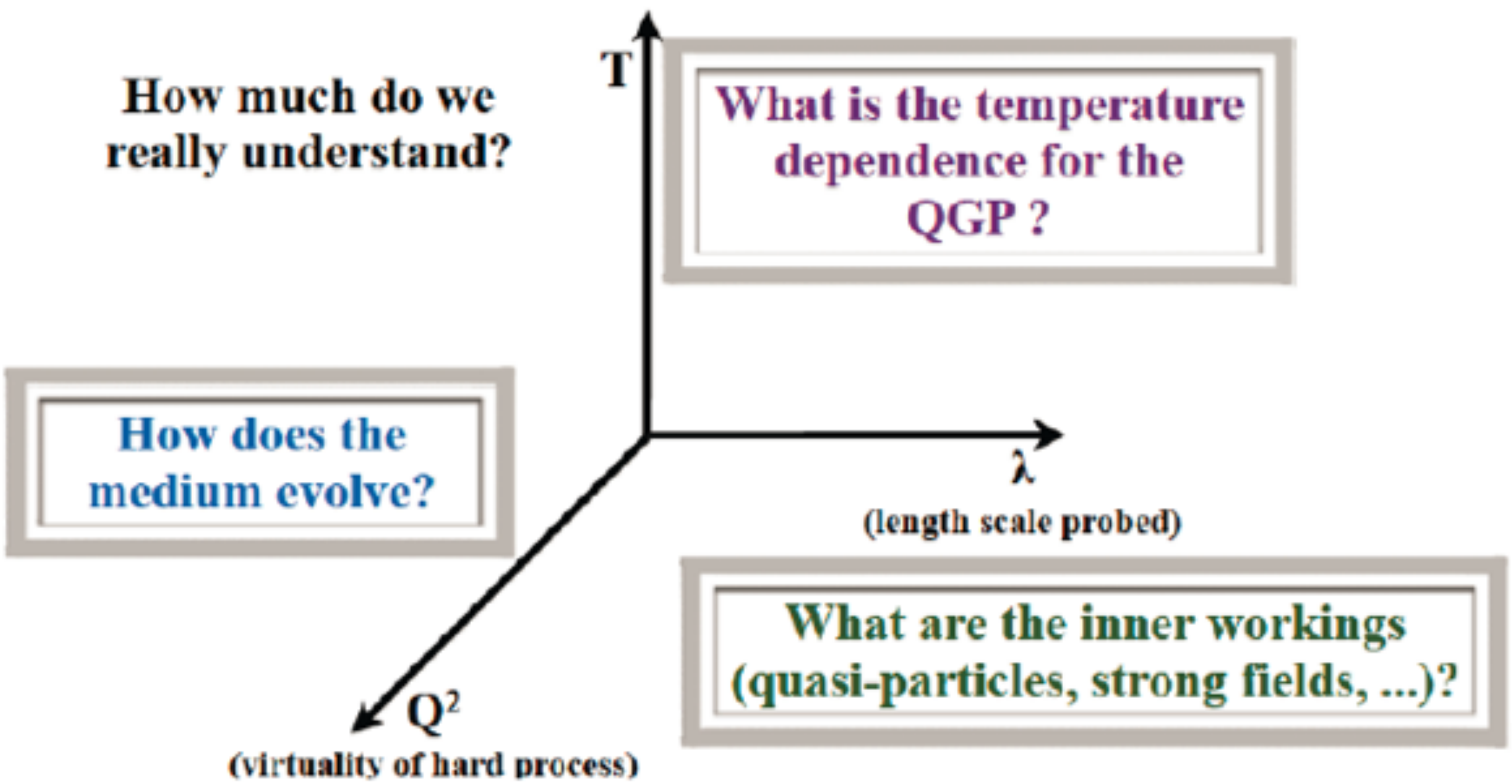
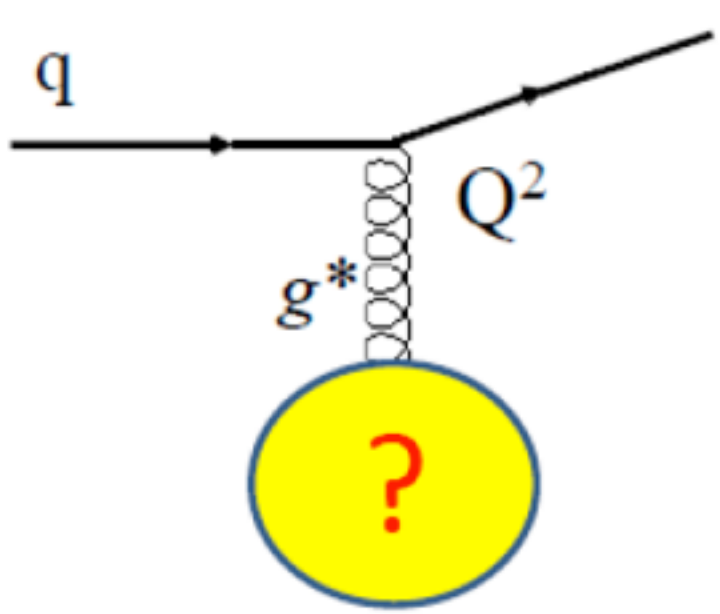
Color screening: Quarkonium states

What we hope to learn

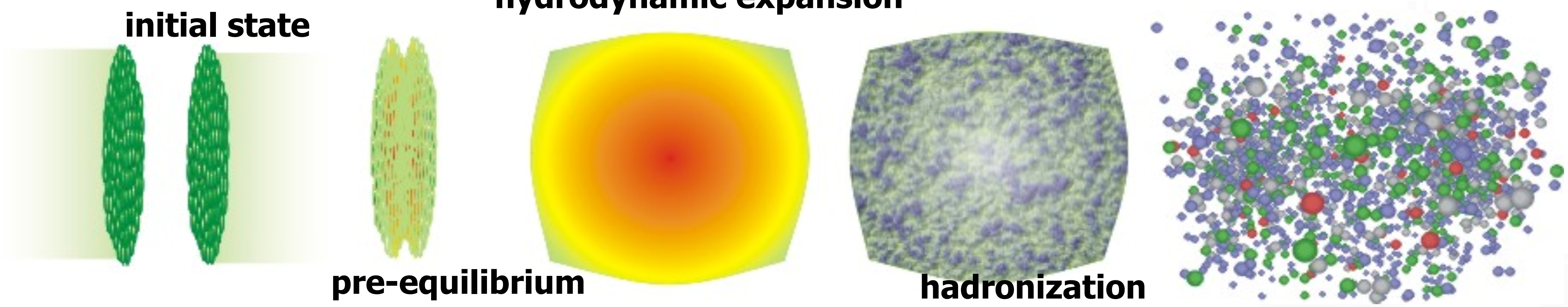
Apart from $\Pi^{\mu\nu}$ all medium properties are expressed as correlators of color gauge fields. They reflect the gluonic structure of the QGP.





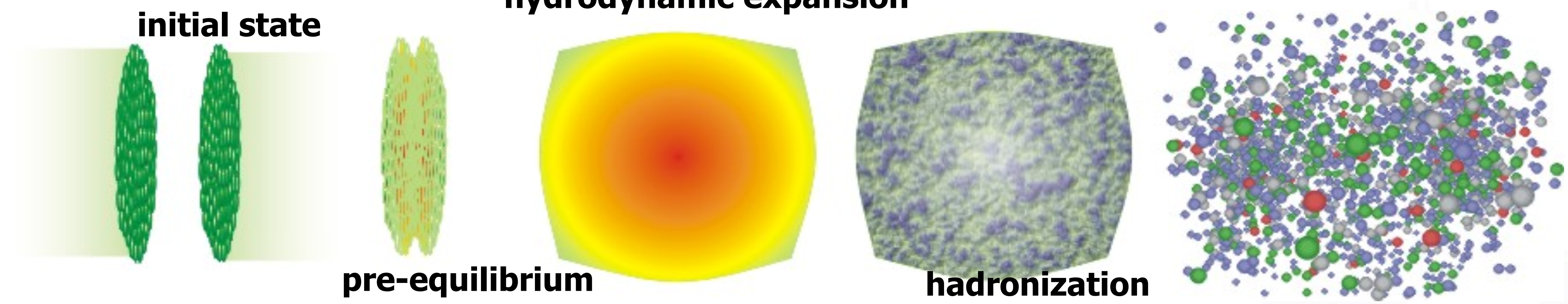
At high Q^2 and/or high T, the QGP is weakly coupled and has a quasiparticulate structure. At which Q^2 (T) does it become strongly coupled? Does it still contain quasiparticles? Can we use hard partons to locate the transition? Which quantities tell us where the transition occurs?

The “standard model”

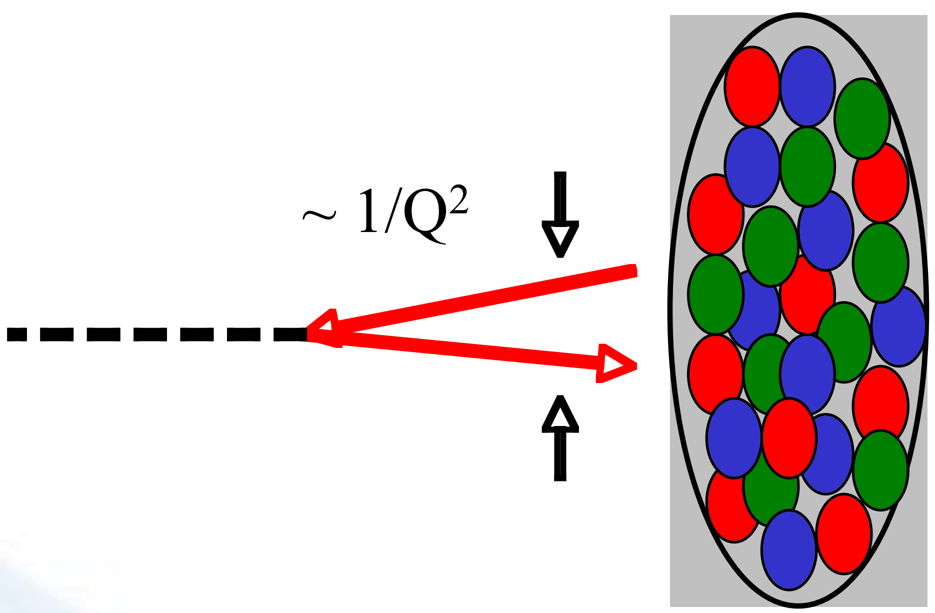


CGC “Glasma” Hydrodynamics Hadronic gas

The “standard model”

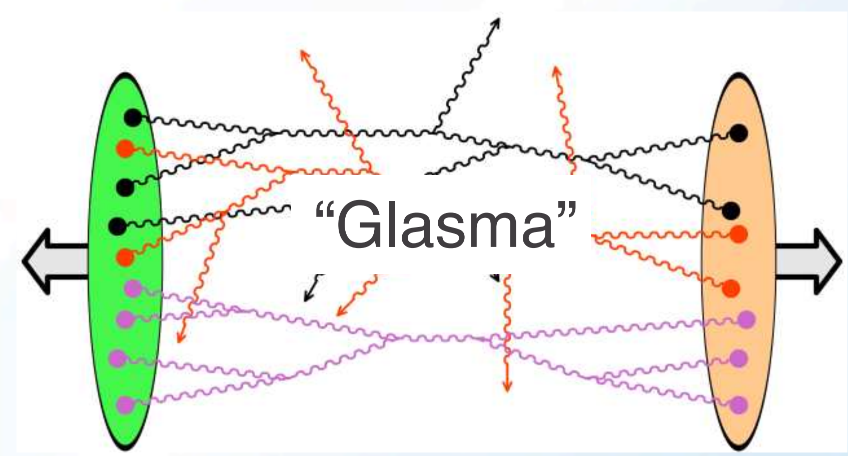


CGC | “Glasma” | Hydrodynamics | Hadronic gas



Color Glass Condensate

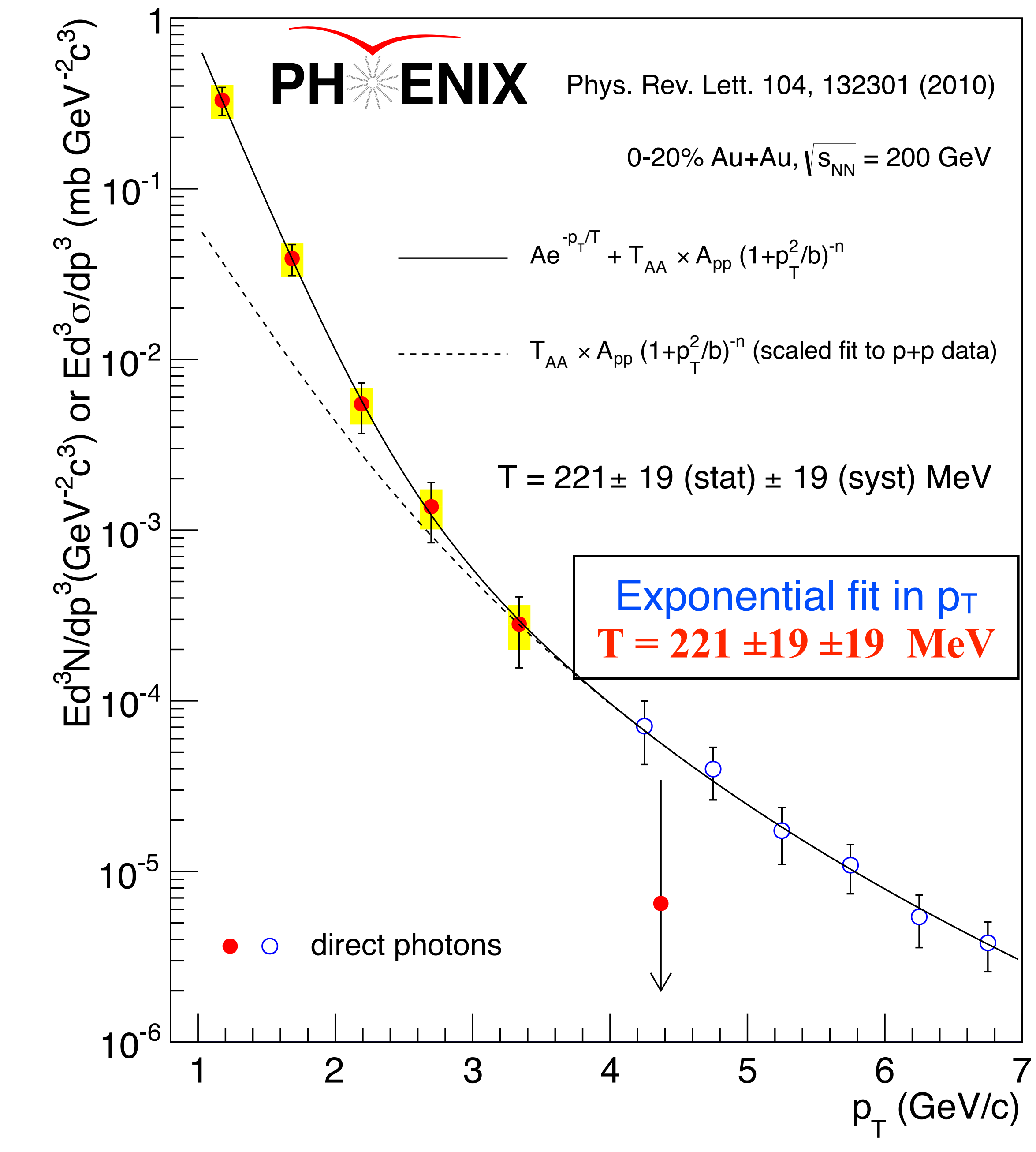
$$\Rightarrow Q_s^2(x, A)$$

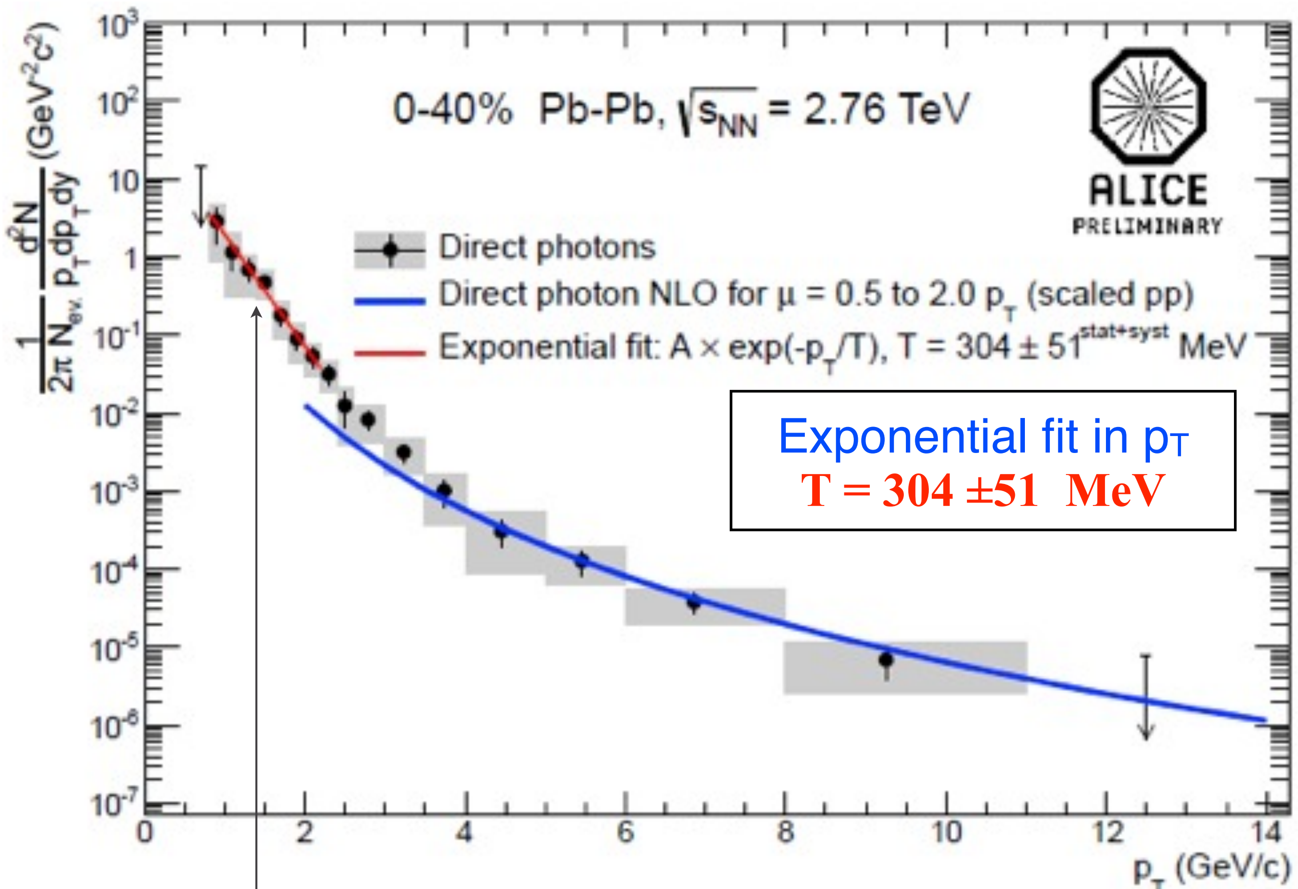


$$\text{gluon density} \times \text{area} \sim \frac{A^{1/3}x^{-0.3}}{Q_s^2} \approx 1$$

$\boxed{\text{Universal saturated state at small } x\text{:} \quad Q_s >> \Lambda_{QCD}}$

Guinness book records





Hydro fits

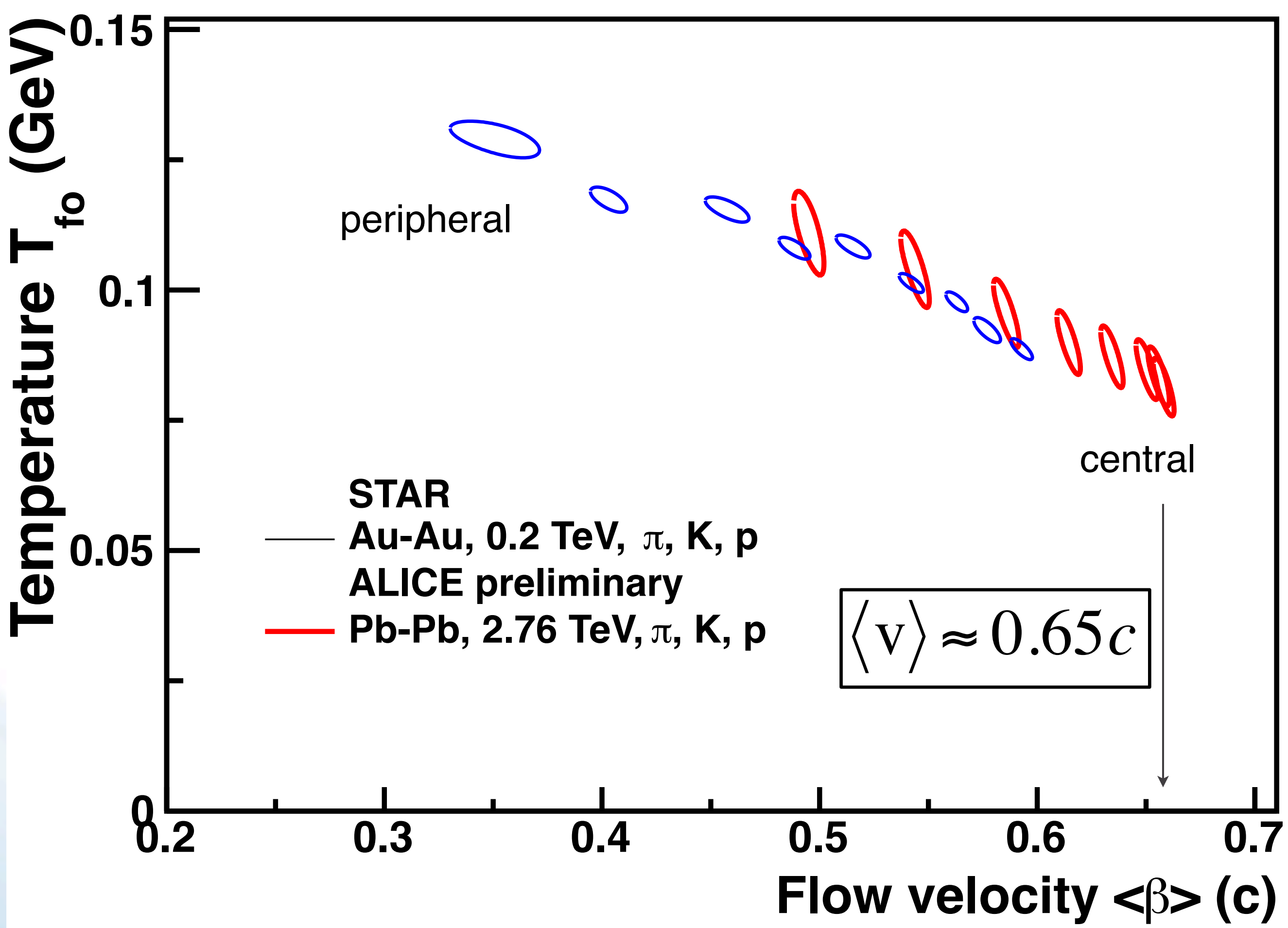
$T_{init} \geq 300$ MeV

New **record "temperature"** measured in Pb+Pb at LHC:

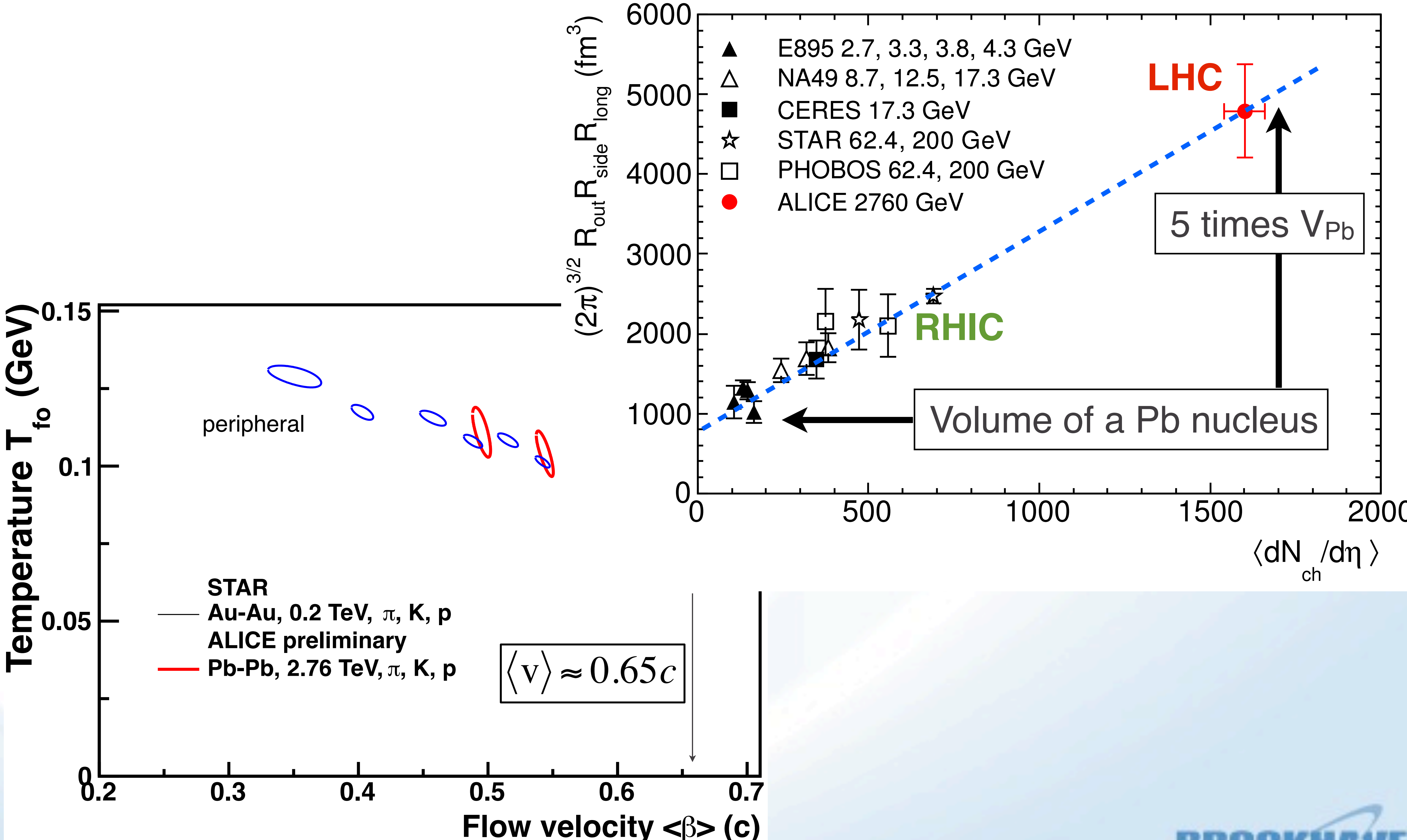
$T_{LHC} = 1.37\, T_{RHIC}$.

Reflects larger initial temperature T_{in}, but not to be identified with T_{in}.

Size and flow



Size and flow

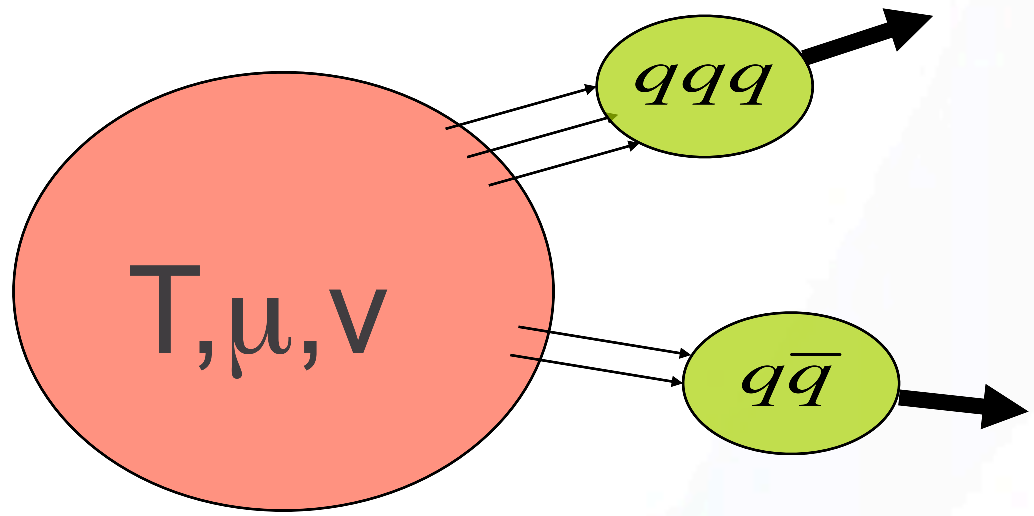


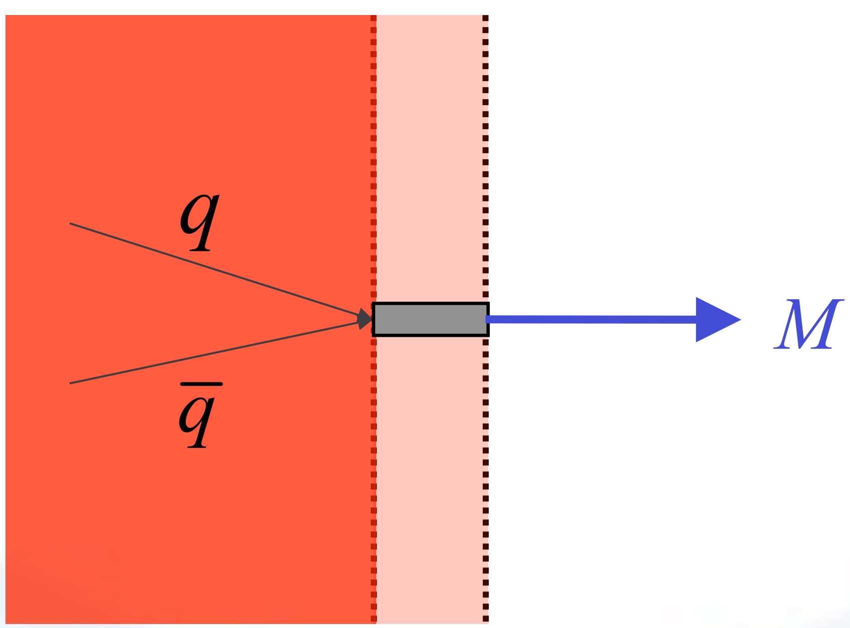
The Hadronizing QGP

Bulk hadronization

Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons

Sudden recombination



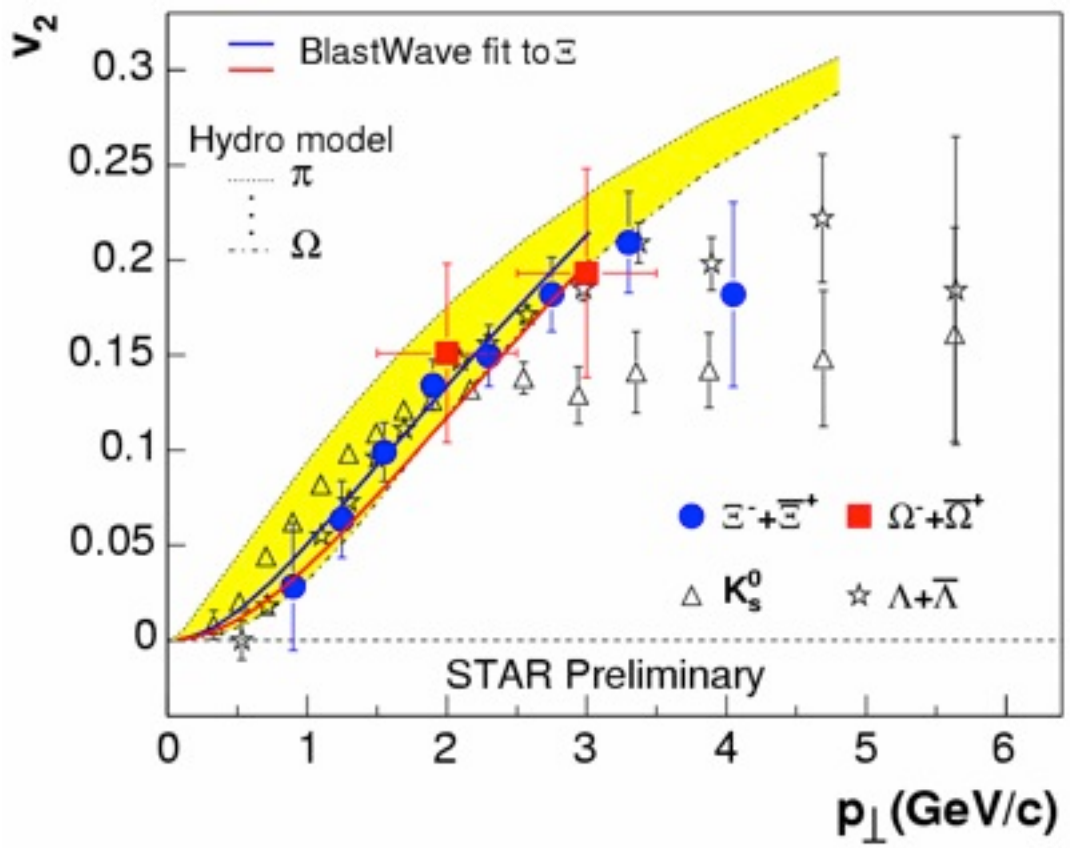


$$v_2^M(p_t) = 2v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^Q\left(\frac{p_t}{3}\right)$$

Quark number scaling of v_2

$$\frac{1}{2} v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3} v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$



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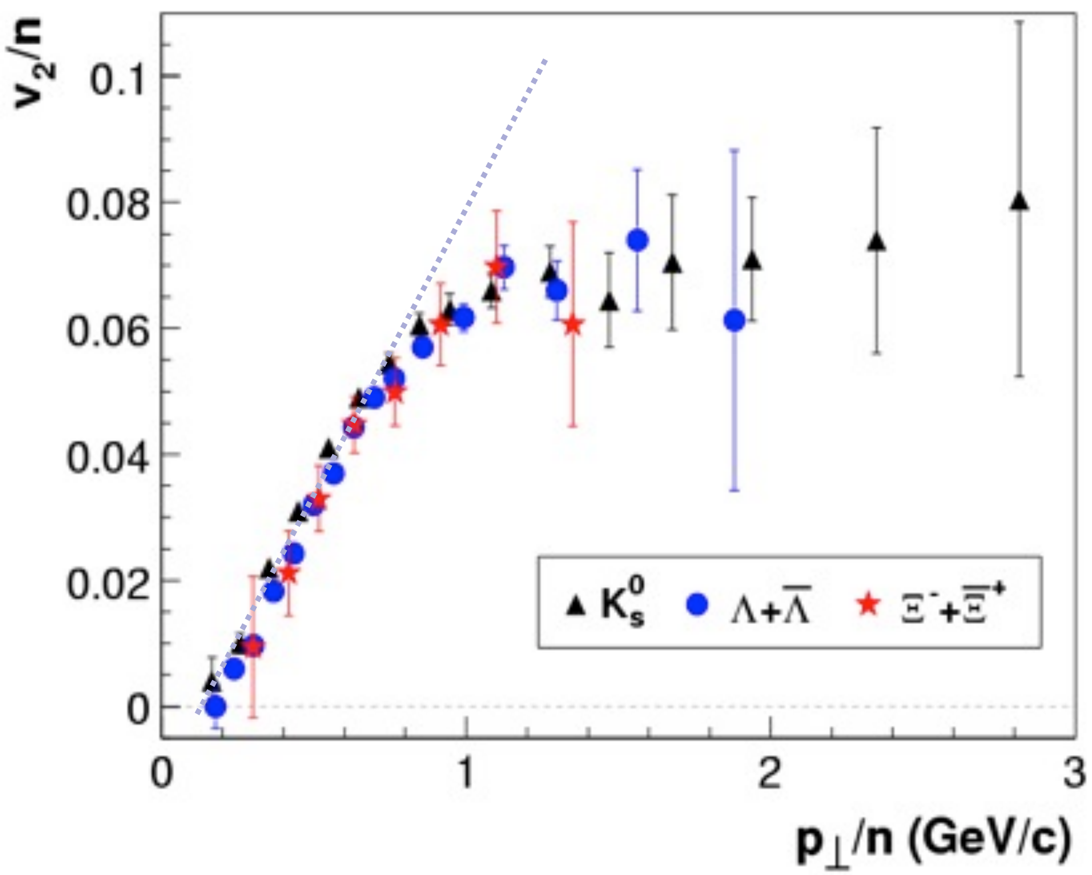
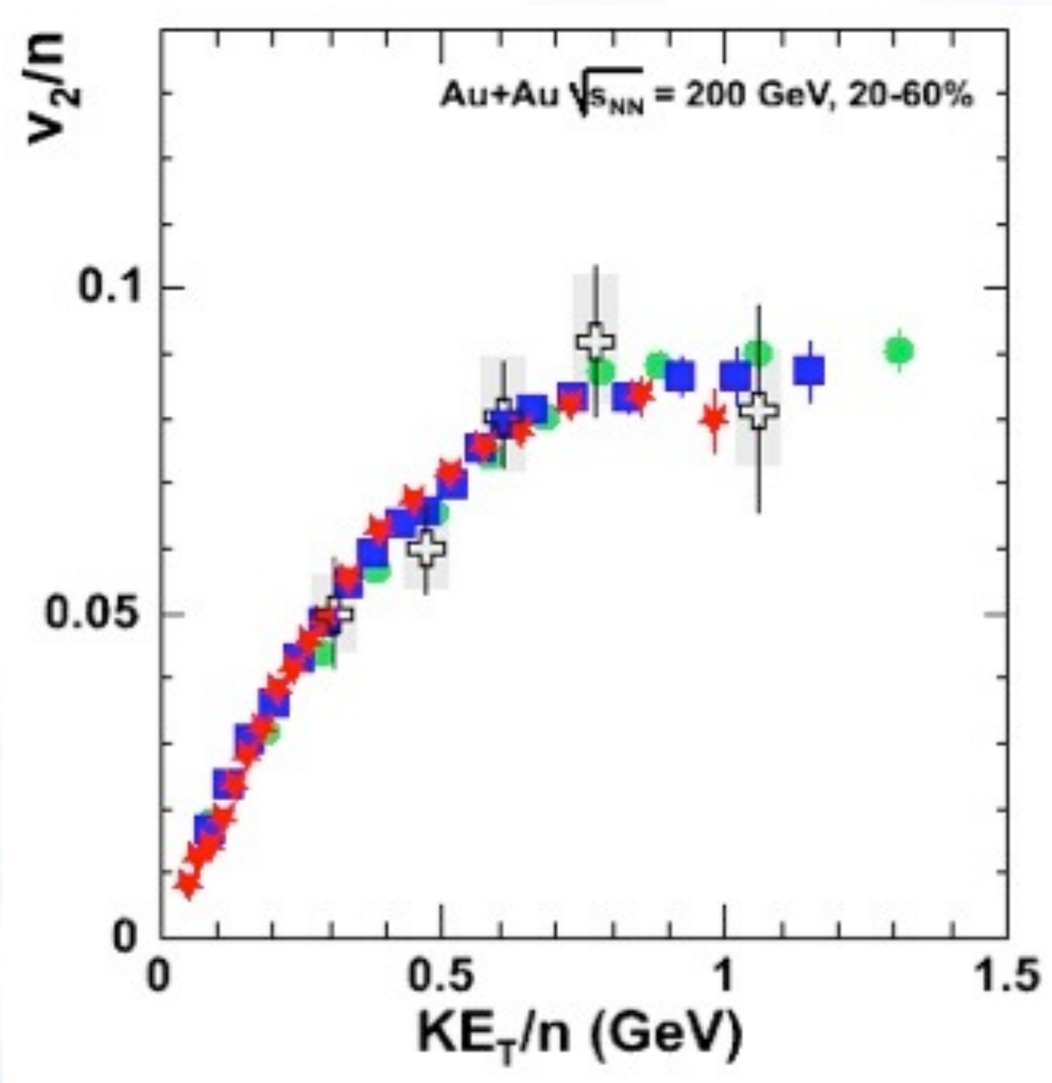




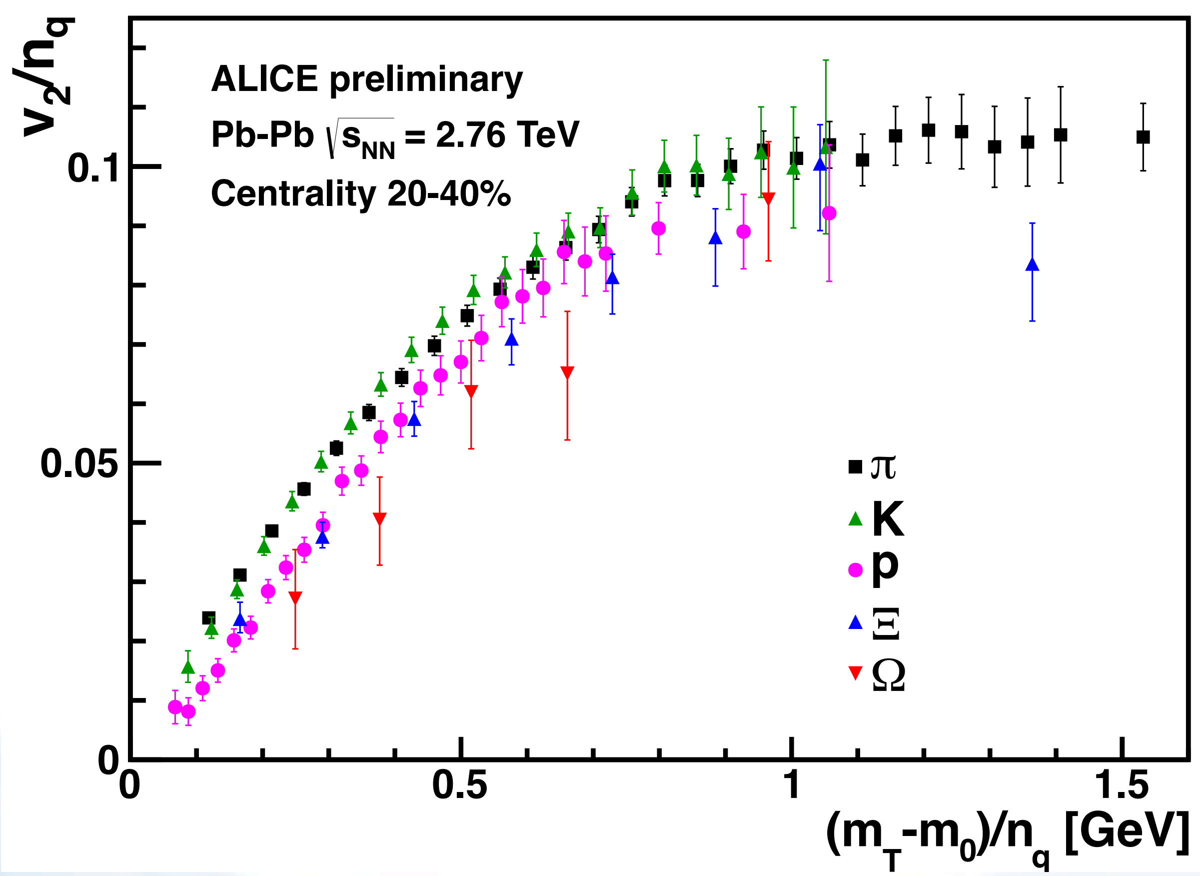
Emitting medium is composed of unconfined, flowing quarks.

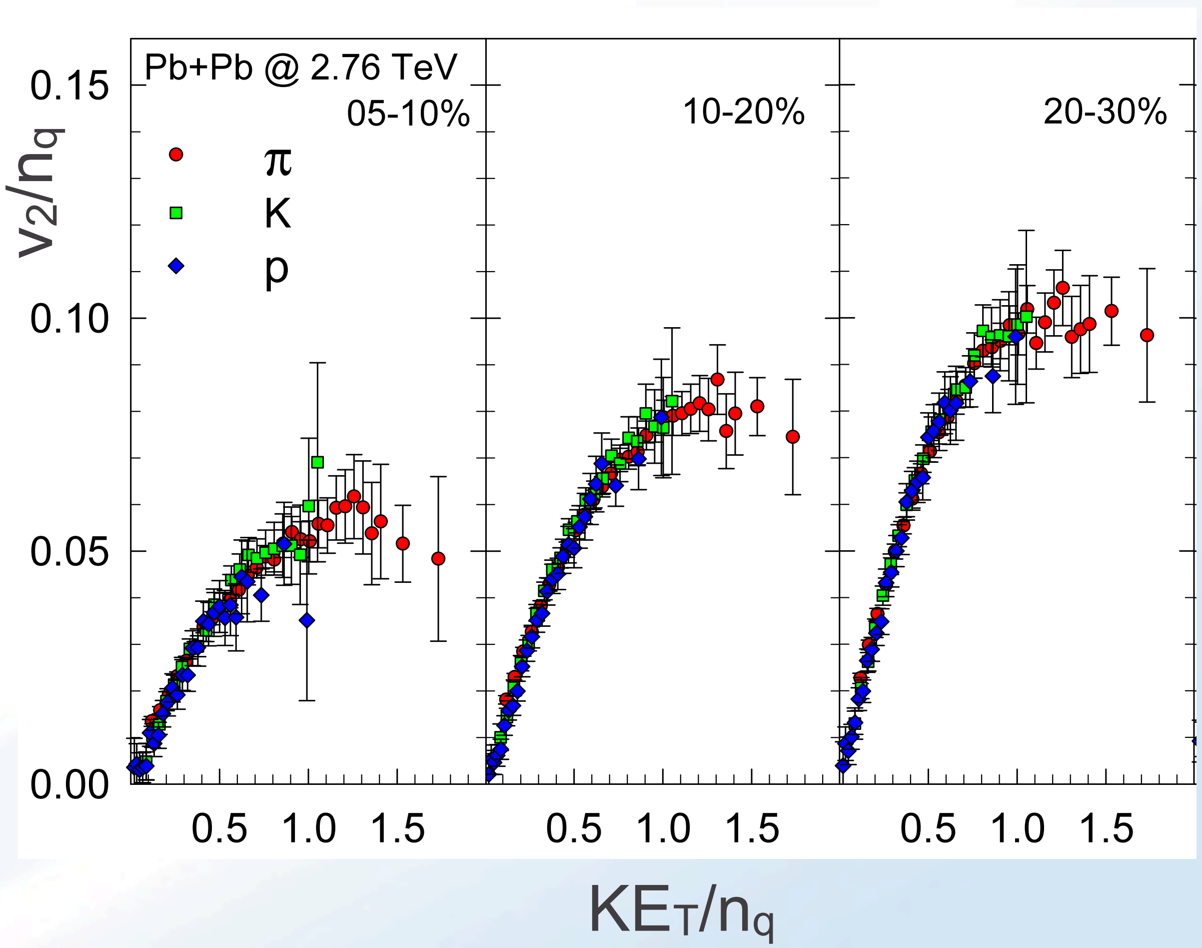
Scaling at LHC?

Hydro works for mesons up to approximately 1.5 GeV/c.

Valence quark scaling appears to fail over whole p_T range.

Lacey et al.: Elliptic flow must be corrected for late hadronic phase contribution. Effect is larger for baryons than mesons. Valence quark scaling works after blue shift correction.





Tuesday, August 13, 13

The "perfect" liquid

Viscous hydrodynamics

Hydrodynamics = effective theory of energy and momentum conservation

energy-momentum tensor = **ideal fluid** + **dissipation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \qquad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu}$$

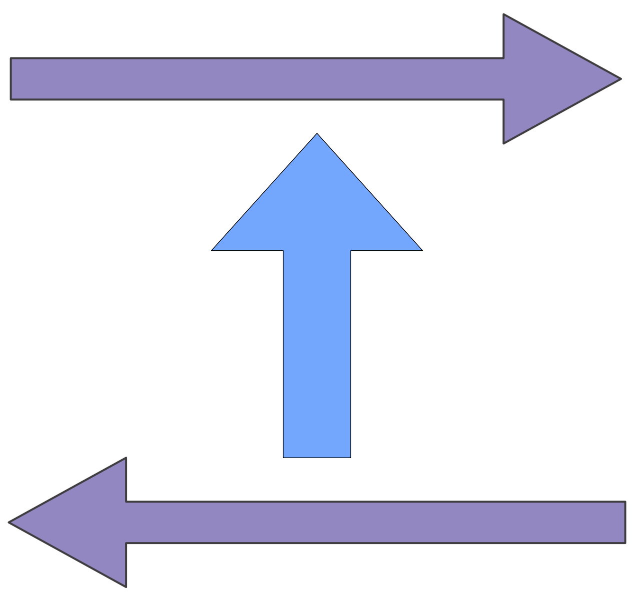
$$\tau_\Pi \left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{du^\lambda}{d\tau} \right] = \eta \left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu}$$

Input: Equation of state $P(\varepsilon)$, shear viscosity, initial conditions $\varepsilon(x,0)$, $u^\mu(x,0)$

Shear viscosity is normalized by density: kinematic viscosity η/ρ.

Relativistically, the appropriate normalization factor is the entropy density $s = (\varepsilon+P)/T$, because the particle density is not conserved: **η/s**.

Shear viscosity



Shear viscosity describes ability to transport momentum across flow gradients! Kinetic theory:

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f \qquad \lambda_f = \frac{1}{n\sigma} \quad \rightarrow \quad \eta \approx \frac{\bar{p}}{3\sigma}$$

$$\sigma \leq \frac{4\pi}{\bar{p}^2} \quad \rightarrow \quad \eta \geq \frac{\bar{p}^3}{12\pi}$$

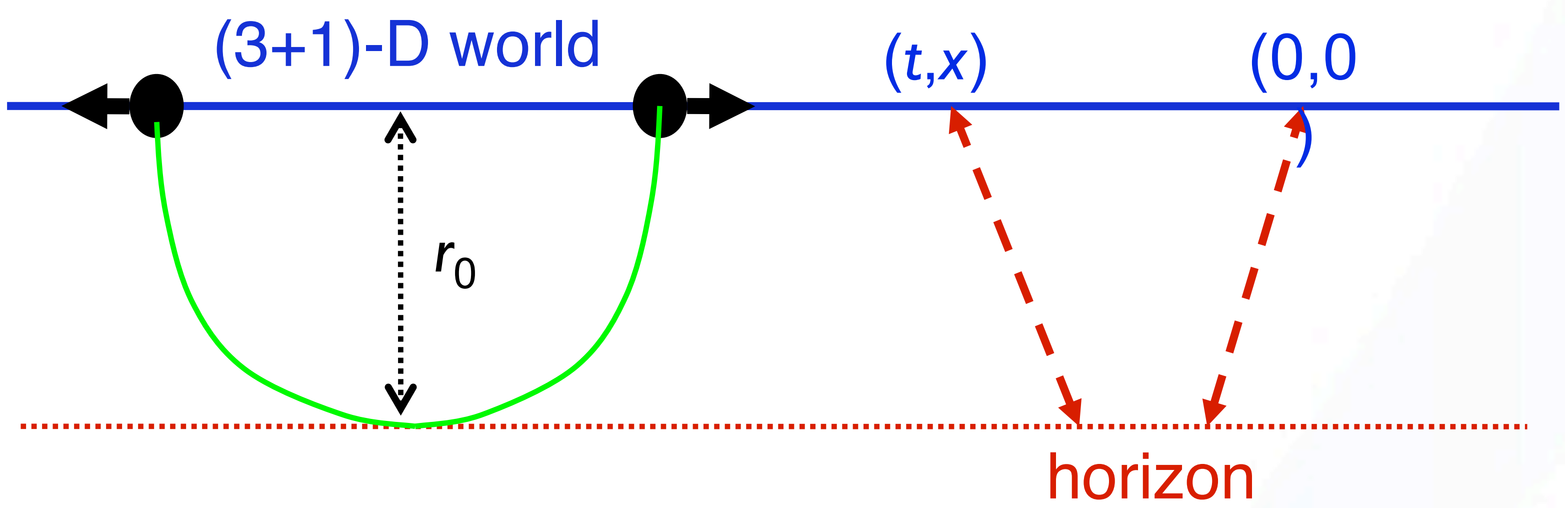
Relativistic system of massless particles:

$$\bar{p} \sim T \quad \rightarrow \quad \bar{p}^3 \sim T^3 \sim s$$

$$\boxed{\Rightarrow \quad \frac{\eta}{s} \geq \text{some lower bound} = \# \cdot \left[\frac{\hbar}{k_B} \right]}$$

Holographic argument

General argument [Kovtun, Son & Starinets, PRL 94 (2005) 111601] based on the holographic duality (AdS/CFT) between thermal QFT and string theory in five-dimensional curved space with a “black-hole” metric.



$$r_0 = \frac{1}{\pi T}$$

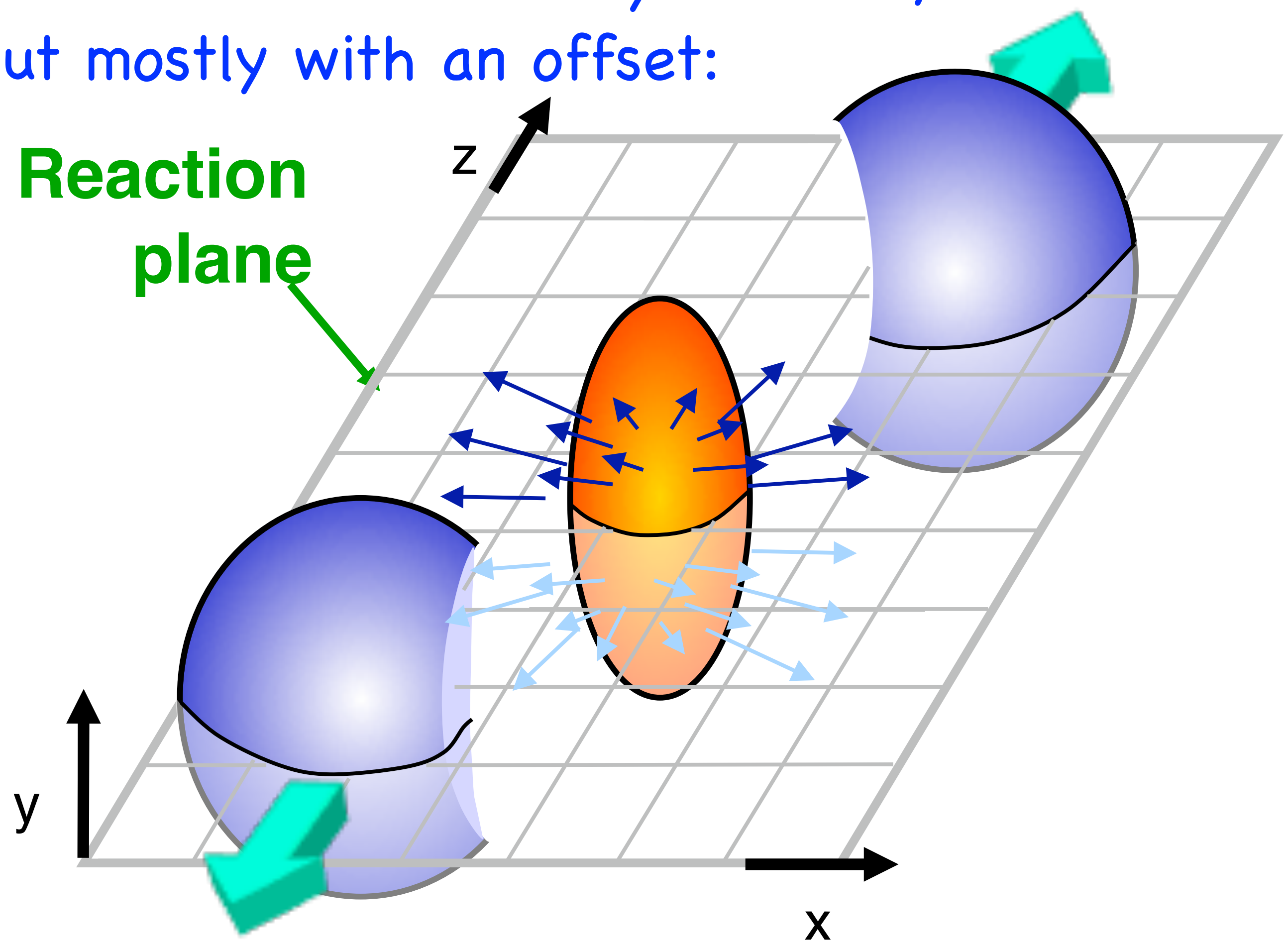
Dissipation in QFT is dual to the absorption of gravitons by the black hole:

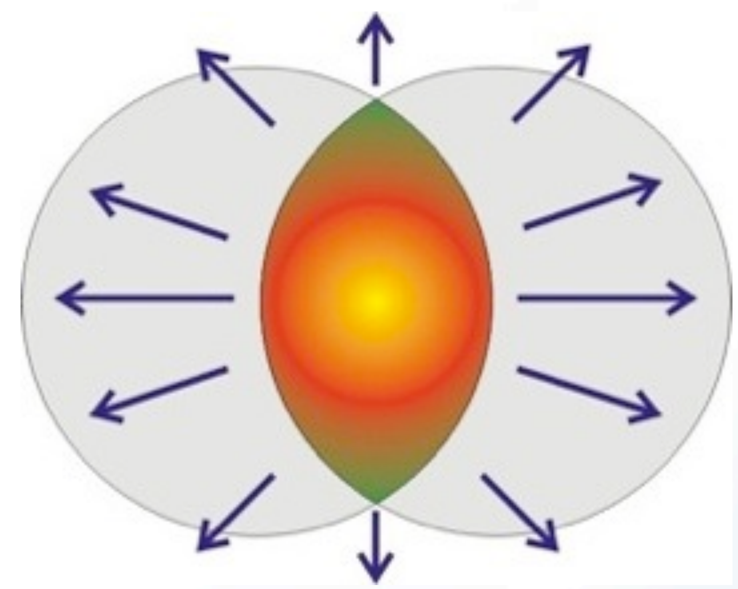
$$\sigma_{\text{abs}}(\omega) = \frac{8\pi G}{\omega}\int dt\, d^3x\, e^{i\omega t}\left\langle\left[T_{xy}(t,\vec{x}),T_{xy}(0,0)\right]\right\rangle \xrightarrow[\omega\to 0]{} a \quad \text{(horizon area)}$$

Thus: $\eta = \dfrac{\sigma_{\text{abs}}(0)}{16\pi G} = \dfrac{a}{16\pi G} = \dfrac{s}{4\pi}$ because $s = \dfrac{a}{4G}$ $\rightarrow$ $\dfrac{\eta}{s} = \dfrac{1}{4\pi}$

Elliptic flow

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

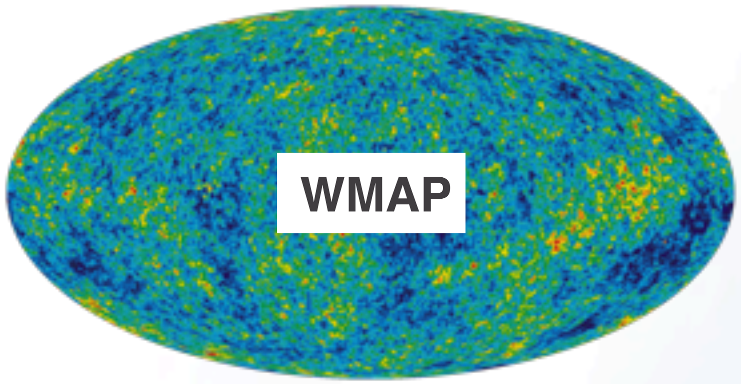
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n \mathrm{v}_n (p_T, \eta) \cos n\left(\phi - \psi_n (p_T, \eta)\right) \right)$$

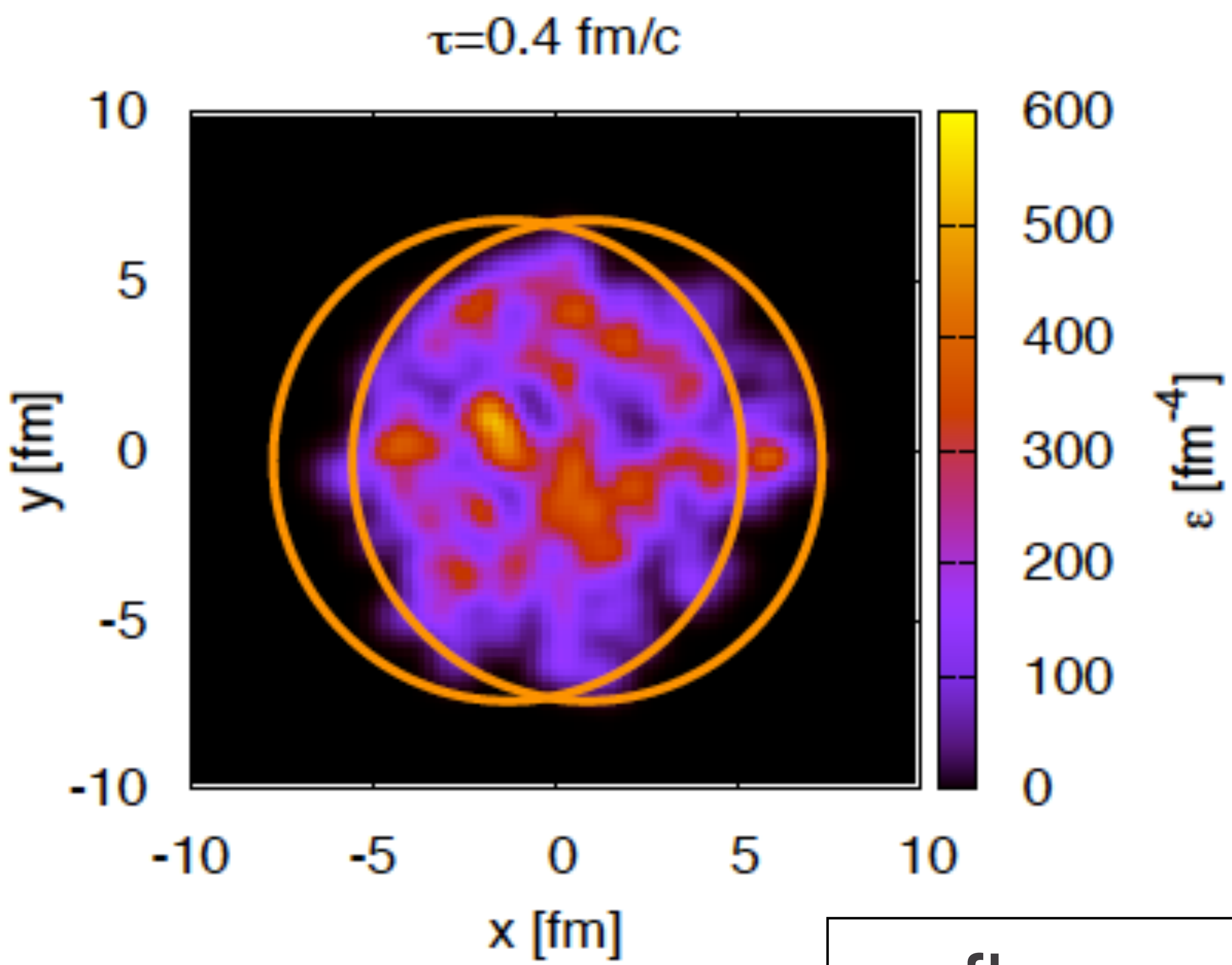
anisotropic flow coefficients

event plane angle

Event-by-event fluctuations

Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0

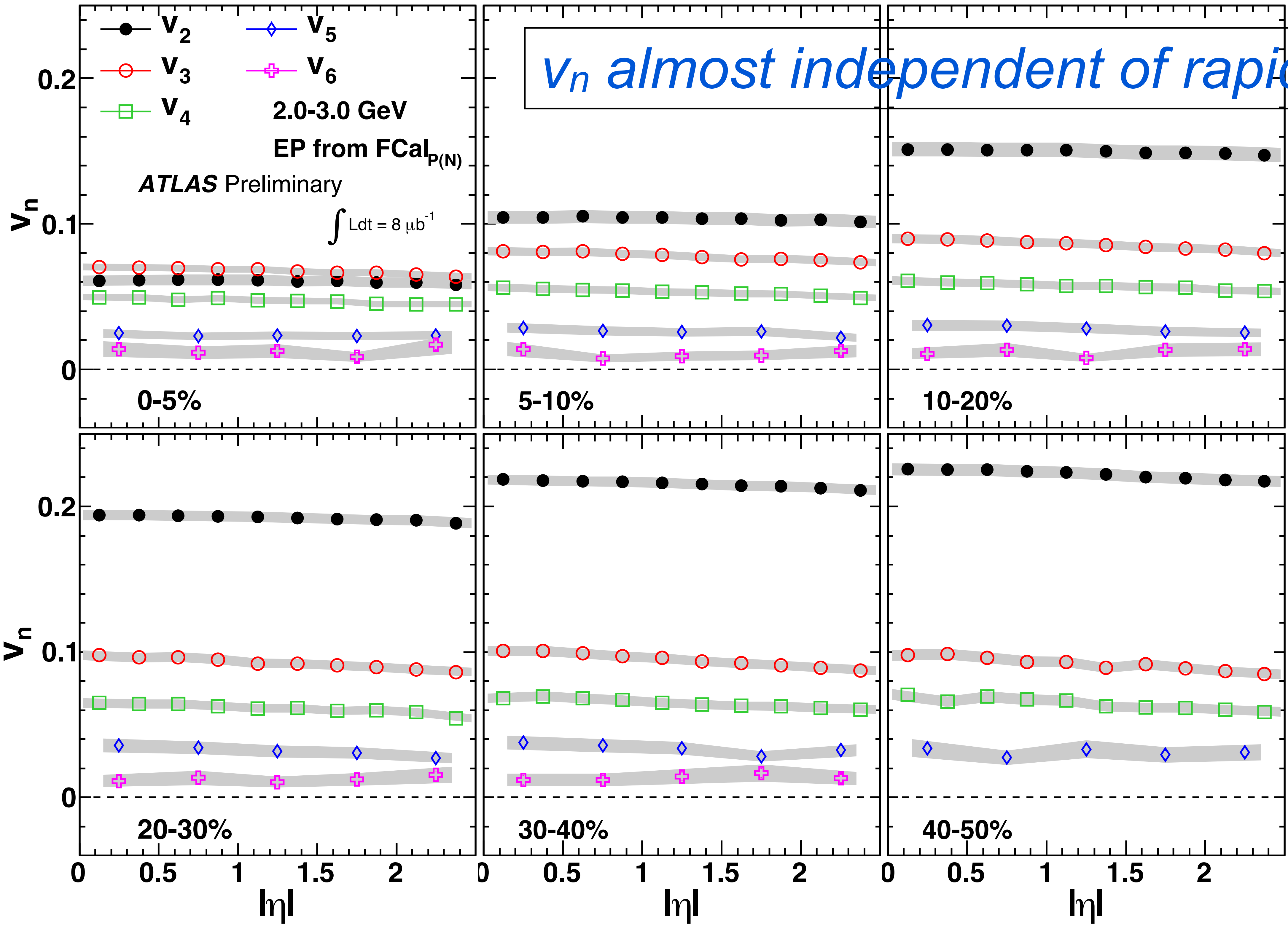




Idea: Energy density fluctuations in transverse plane from initial state quantum fluctuations. These thermalize to different temperatures locally and then propagate hydrodynamically to generate angular flow velocity fluctuations in the final state.

⇒ flows v_1, v_2, v_3, v_4,...

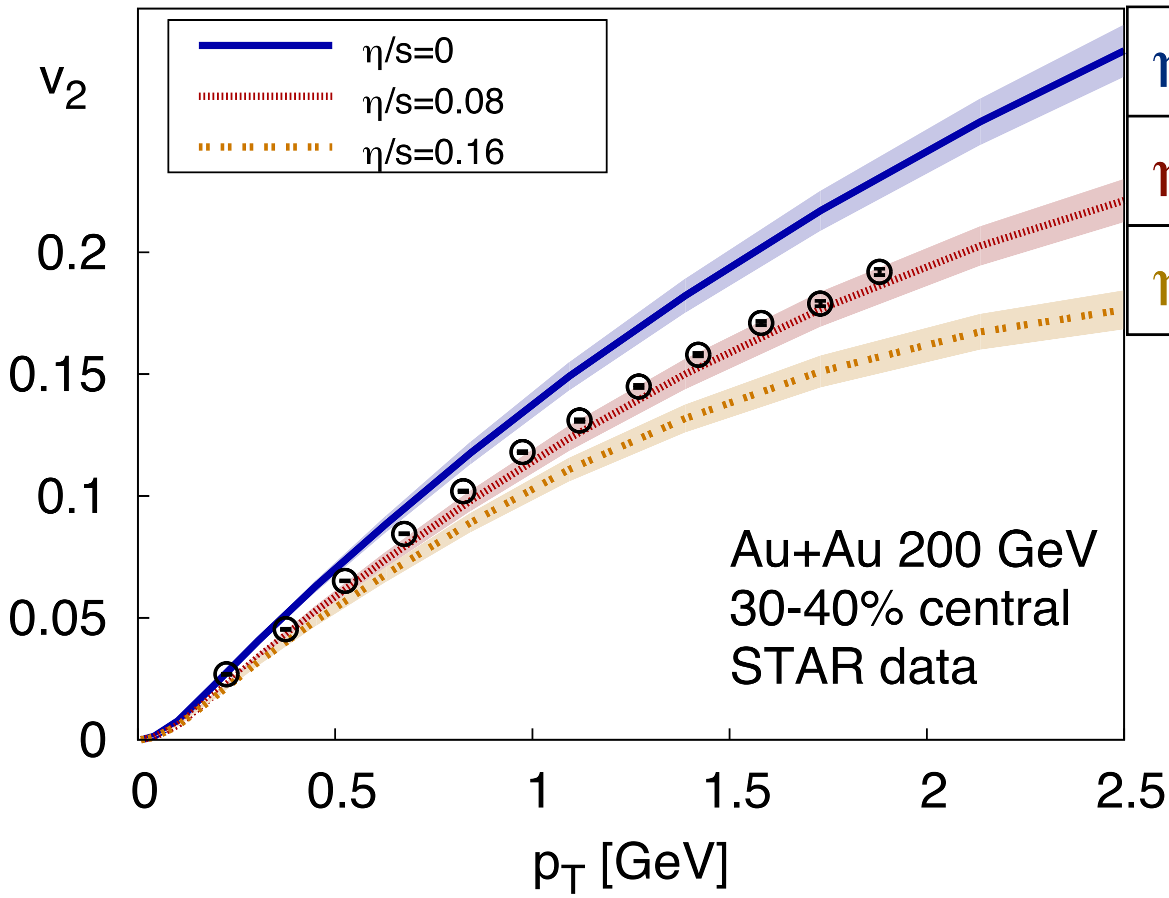
v_n (n = 2,...,6)



v_n almost independent of rapidity

Elliptic flow “measures” η_{QGP}

Schenke, Jeon, Gale, PRL 106 (2011) 042301



$\eta/s = 0$

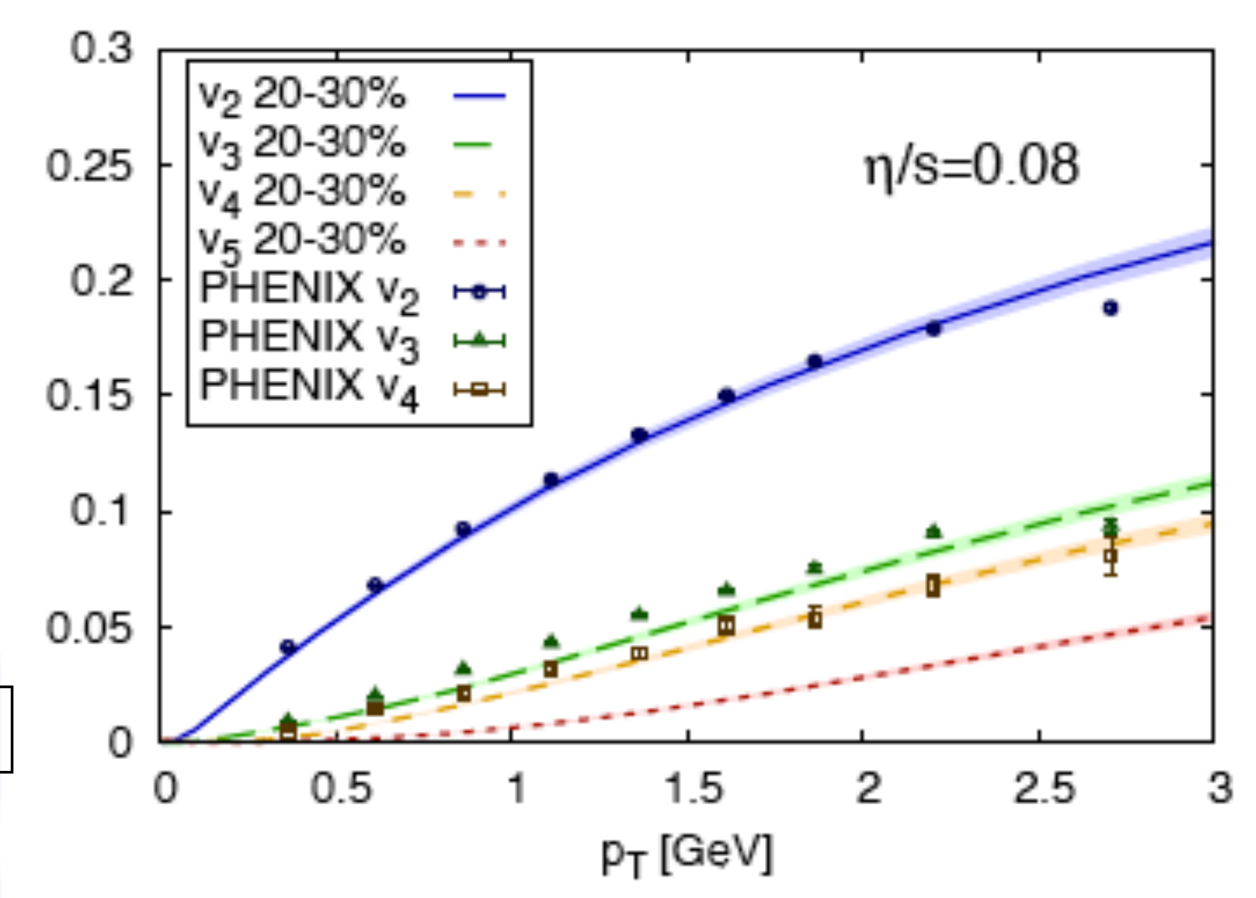
$\eta/s = 1/4\pi$

$\eta/s = 2/4\pi$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \longrightarrow 1/4\pi$

aka: the “perfect” liquid

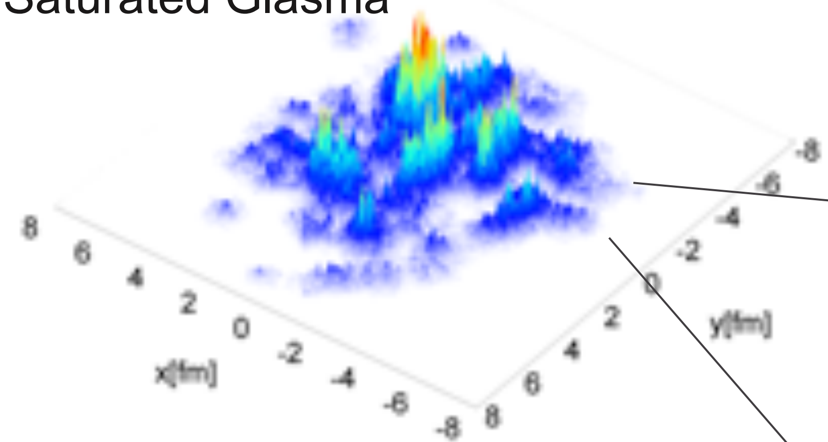


Schenke, Jeon, Gale, PRC 85 (2012) 024901

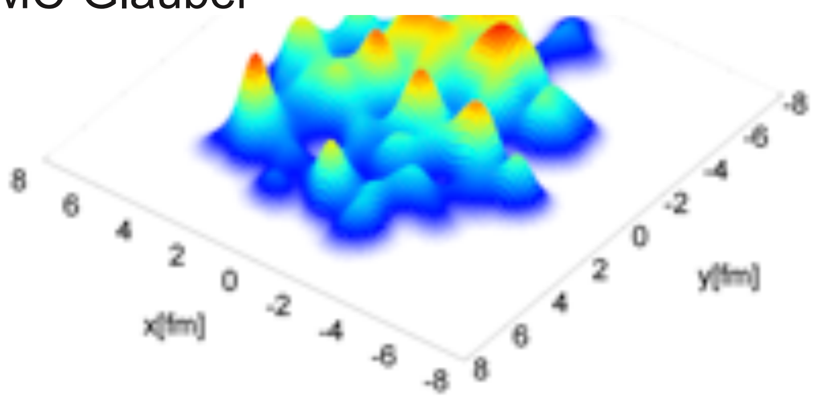
RHIC vs. LHC

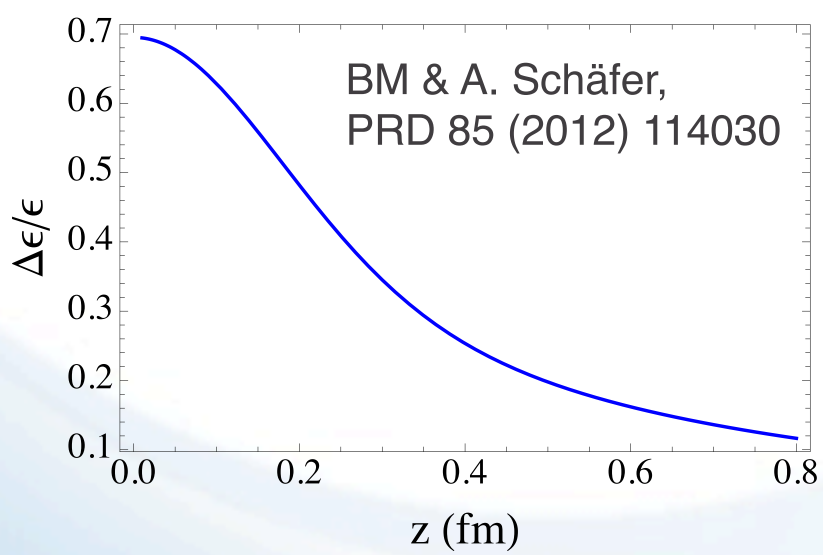
Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330

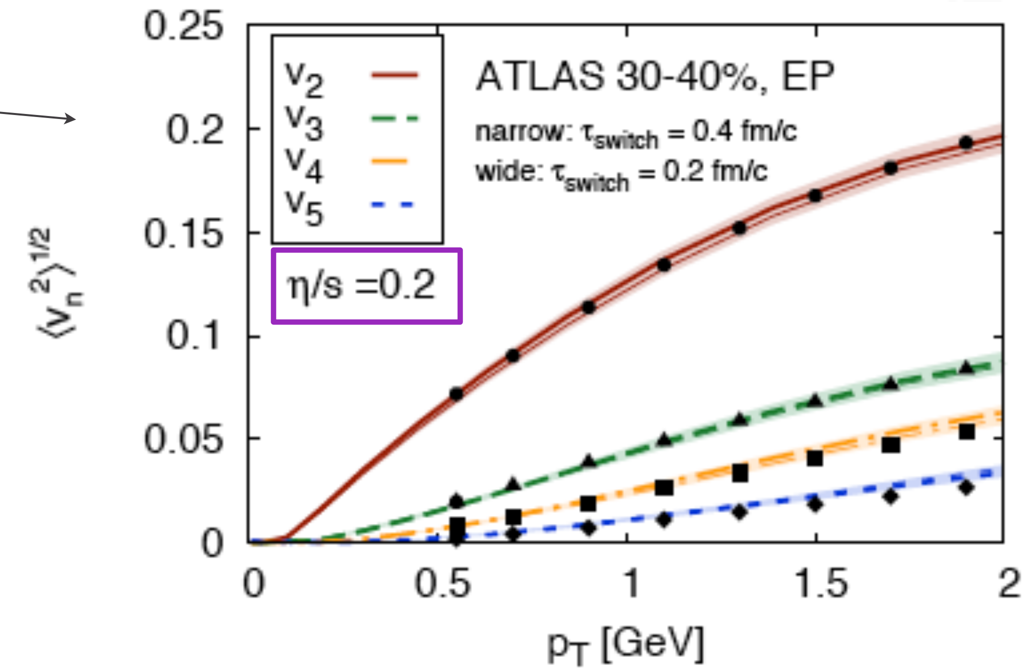
Saturated Glasma



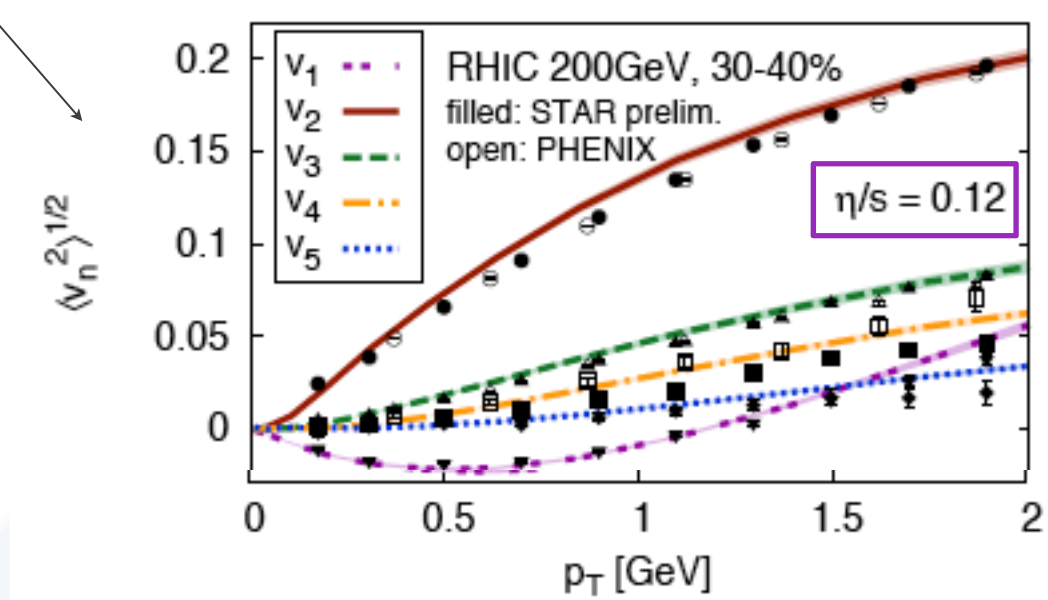
MC-Glauber







LHC

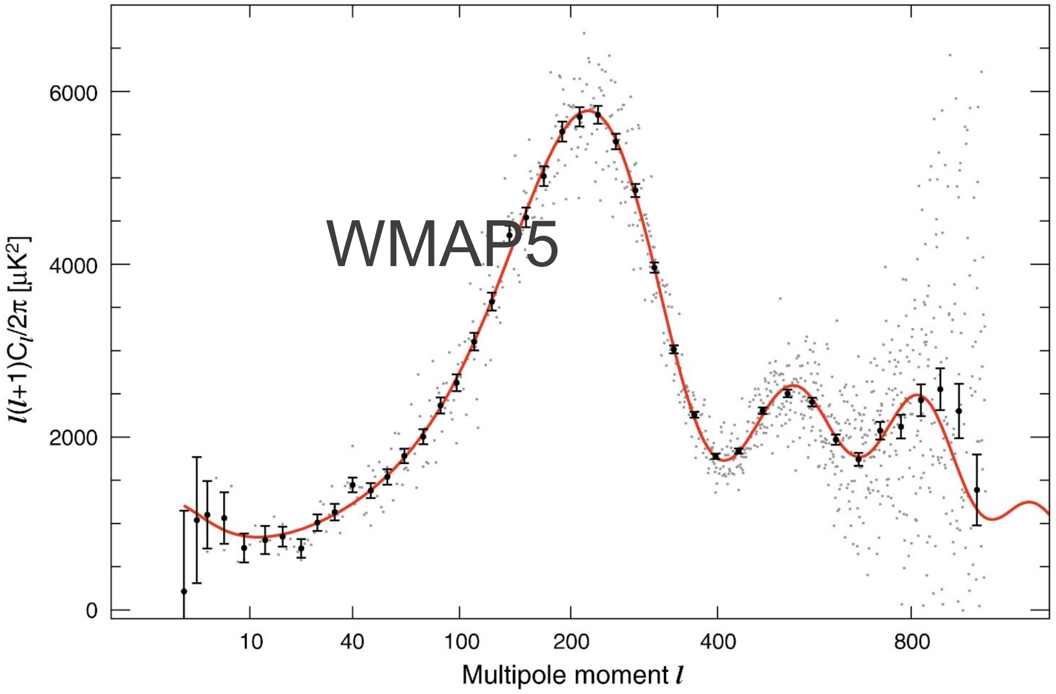


RHIC

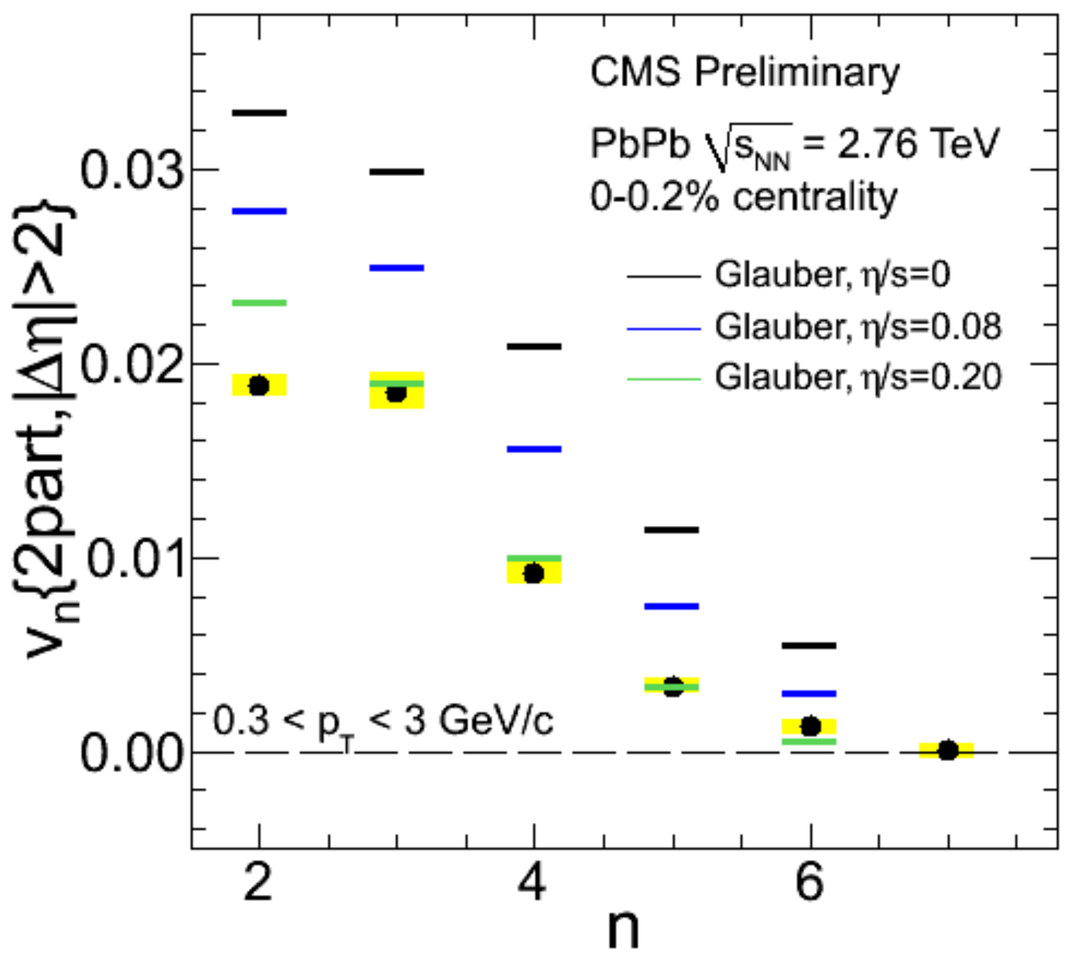
Fluctuation spectrum

Can different distributions of various eccentricities in different collision systems be used to discriminate between energy deposition models / theories?

Can the power spectrum of v_n be used to determine η/s and v_{sound} ?



M. Luzum et al.



The RHIC/LHC advantage:
There are many knobs to turn, not just a single universe to observe.

Future challenges

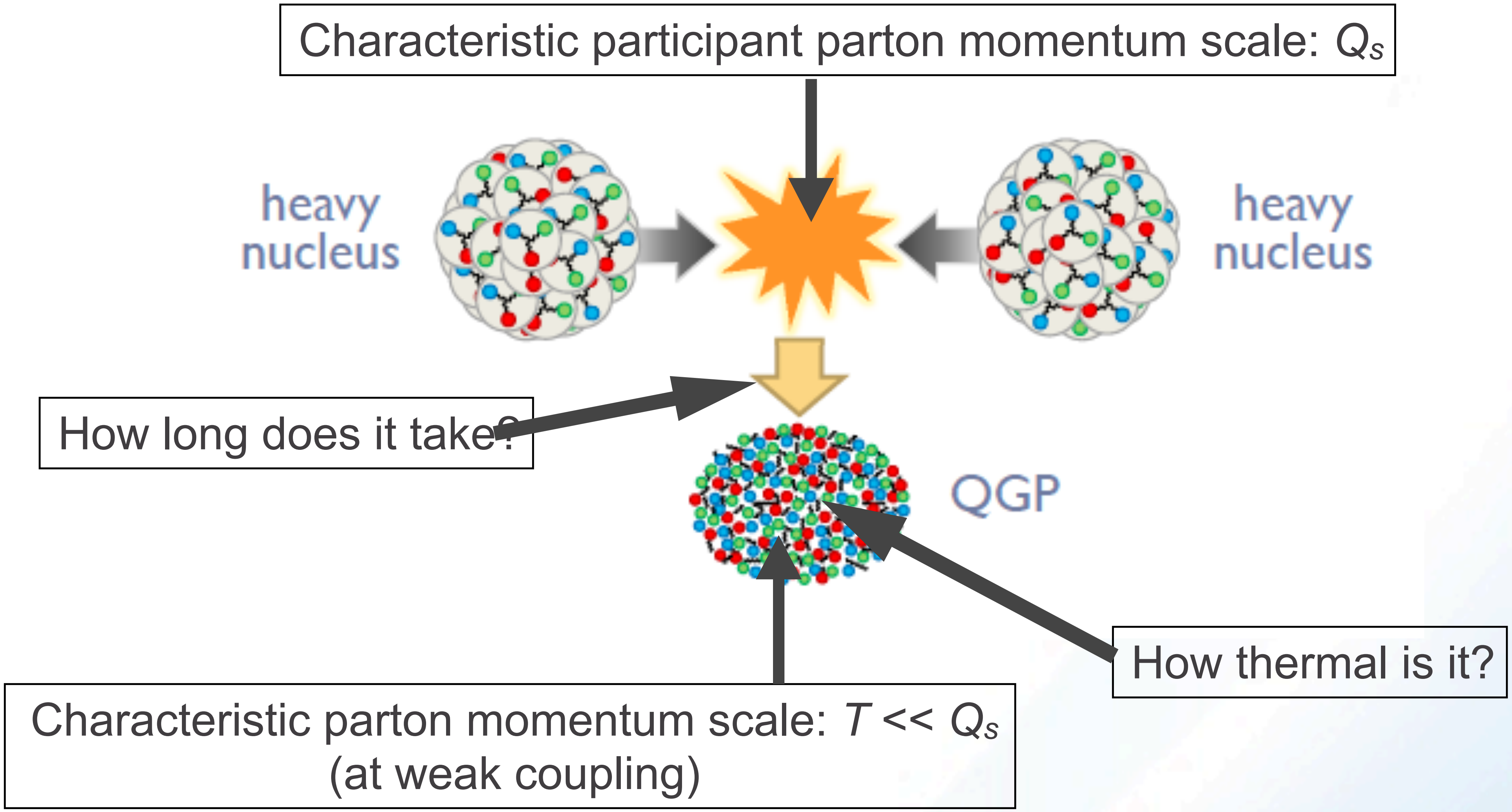
- Determination of transverse profile
  - Can gluon saturation provide a firm prediction?
    - Can we use d+Au (p+Pb) collisions to constrain CGC approach?
    - Are there theoretically founded alternatives?

- Check of system independence
  - Cu+Cu, Cu+Au, U+U
    - Very important to demonstrate theoretical control (RHIC!)

- Anomalous viscosity?
  - Dynamical generation of color fields during thermalization?
  - Do glasma properties survive into hydro stage?

Thermalization

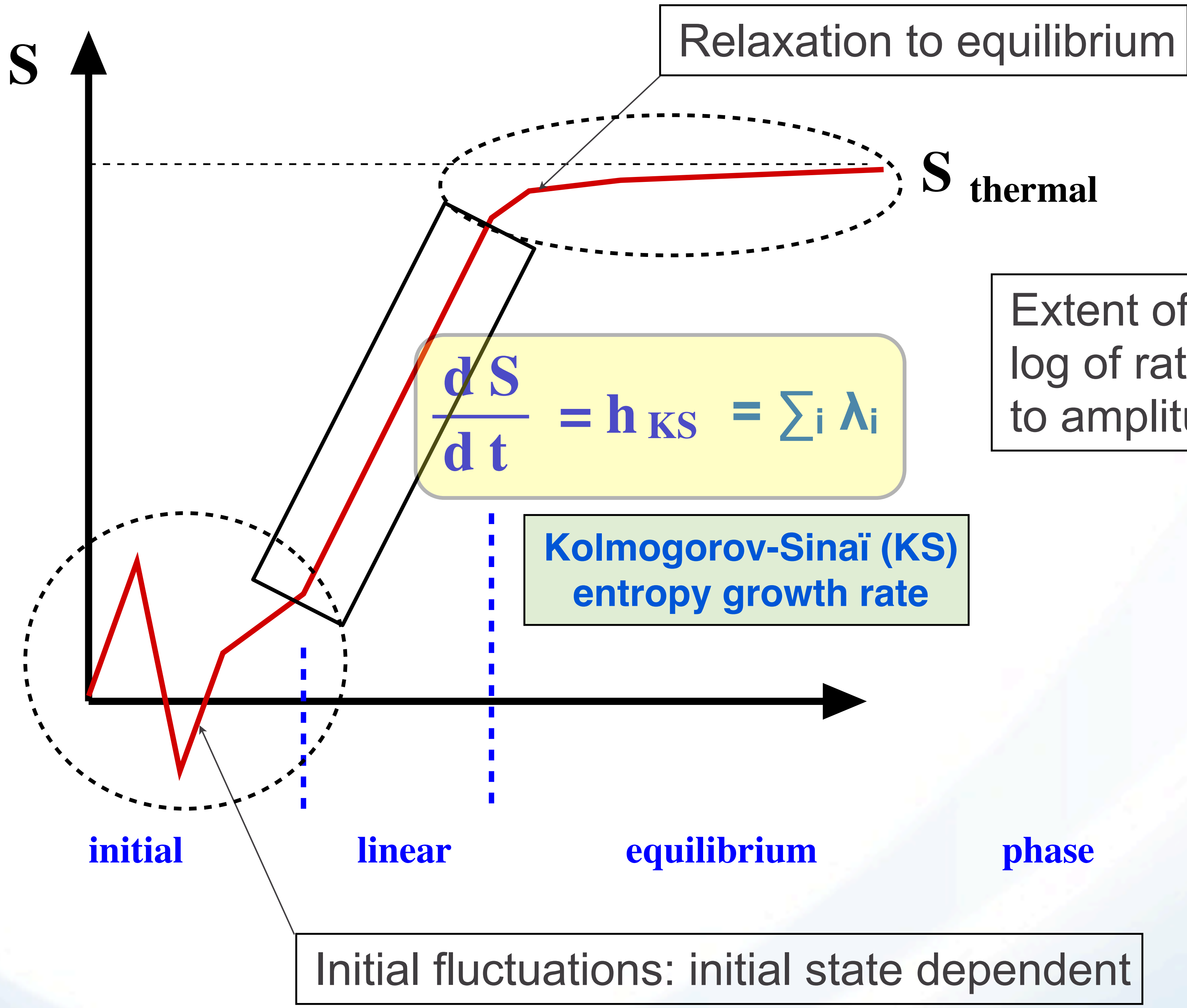
Thermalization



How does the thermalization process work at strong coupling?

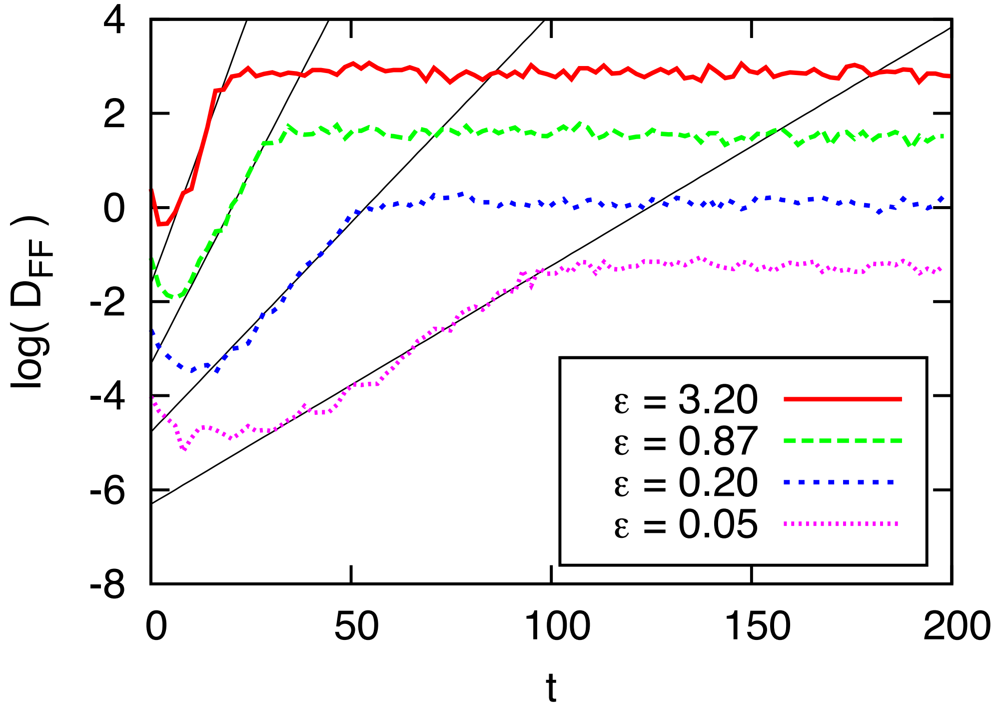
If not “bottom up”, what else?

Classical picture

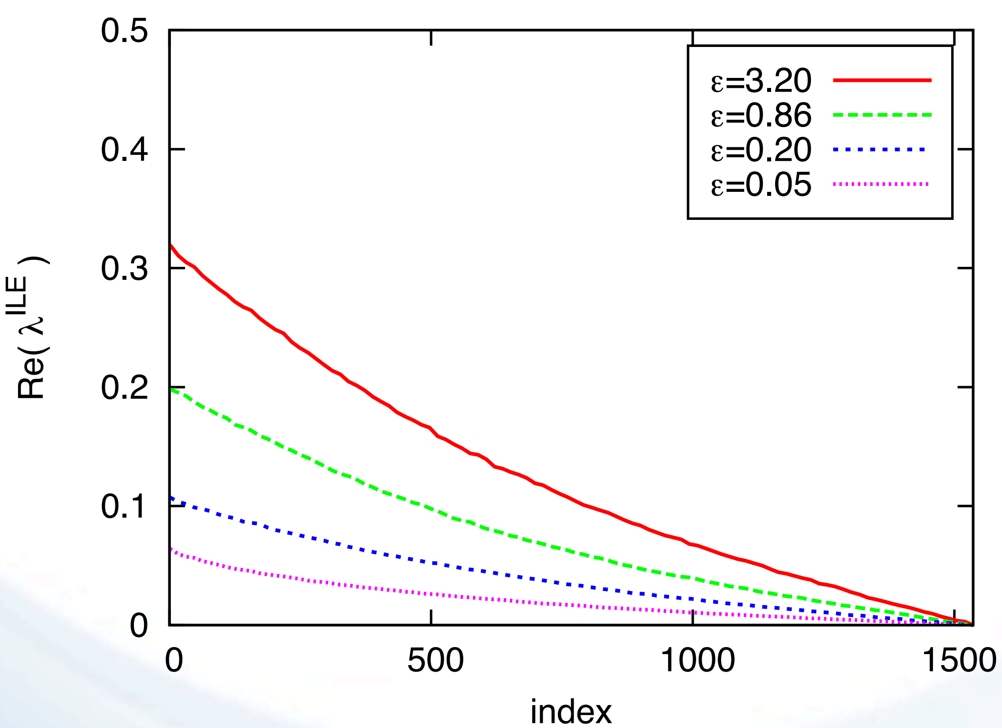


Extent of linear region depends on log of ratio of thermal fluctuations to amplitude of initial fluctuations.

Classical lattice SU(3)



T. Kunihiro, BM, A. Ohnishi, A. Schäfer, T. Takahashi & A. Yamamoto, PRD 82 (2010) 114015



ILE = Intermediate Lyapunov exponents:
= Growth rate of distance between neighboring gauge field config's

Lattice gauge fields exhibit extensive spectrum of positive Lyapunov exponents.

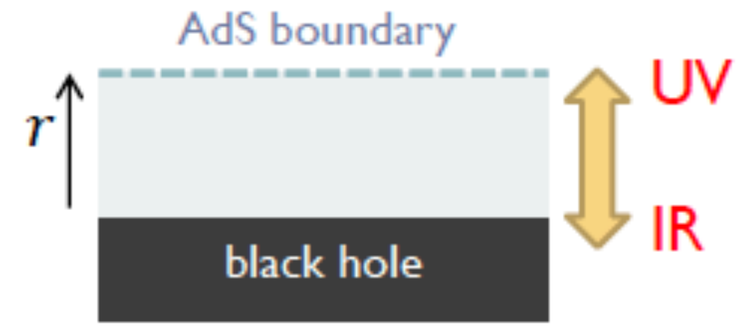
➥ Finite KS entropy density.

AdS/CFT dictionary

- Want to study strongly coupled phenomena in QCD
- Toy model: $\mathcal{N} = 4\ SU(N_c)$ SYM

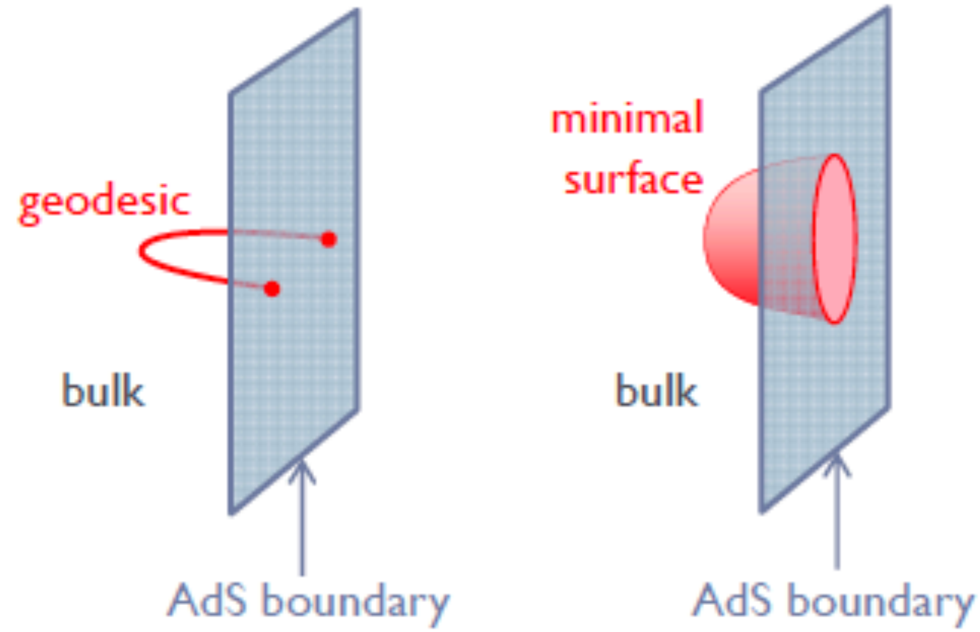
$\mathcal{N} = 4$ SYM	holo. dual ⟺ AdS/CFT	String theory in AdS_5
Strong coupling	⟷	Weak coupling
Vacuum	⟷	Empty AdS_5
Thermal state (equilibrated plasma)	⟷	AdS BH
Thermalization	⟷	BH formation
HI collision	⟷	Energy injection

$$\left(\frac{R_{AdS}}{l_s}\right)^4 = g_{YM}^2 N_c \equiv \lambda$$



Thermality probes

- 2-point function
  - $\langle \mathcal{O}(x)\mathcal{O}(x)\rangle$
  - Bulk: geodesic (1D)
- Wilson line
  - $W = P\{\exp[\int_C A_\mu(x)dx^\mu]\}$
  - Bulk: minimal surface (2D)
- Entanglement entropy
  - $S_A = -\mathrm{Tr}_A[\rho_A \log \rho_A], \quad \rho_A = \mathrm{Tr}_B[\rho_{\mathrm{tot}}]$
  - Bulk: codim-2 hypersurface (same dimension as boundary space)



Use semiclassical approximation

For details: *V. Balasubramanian, et al.*, PRL **106**, 191601 (2011); PRD 84, 026010

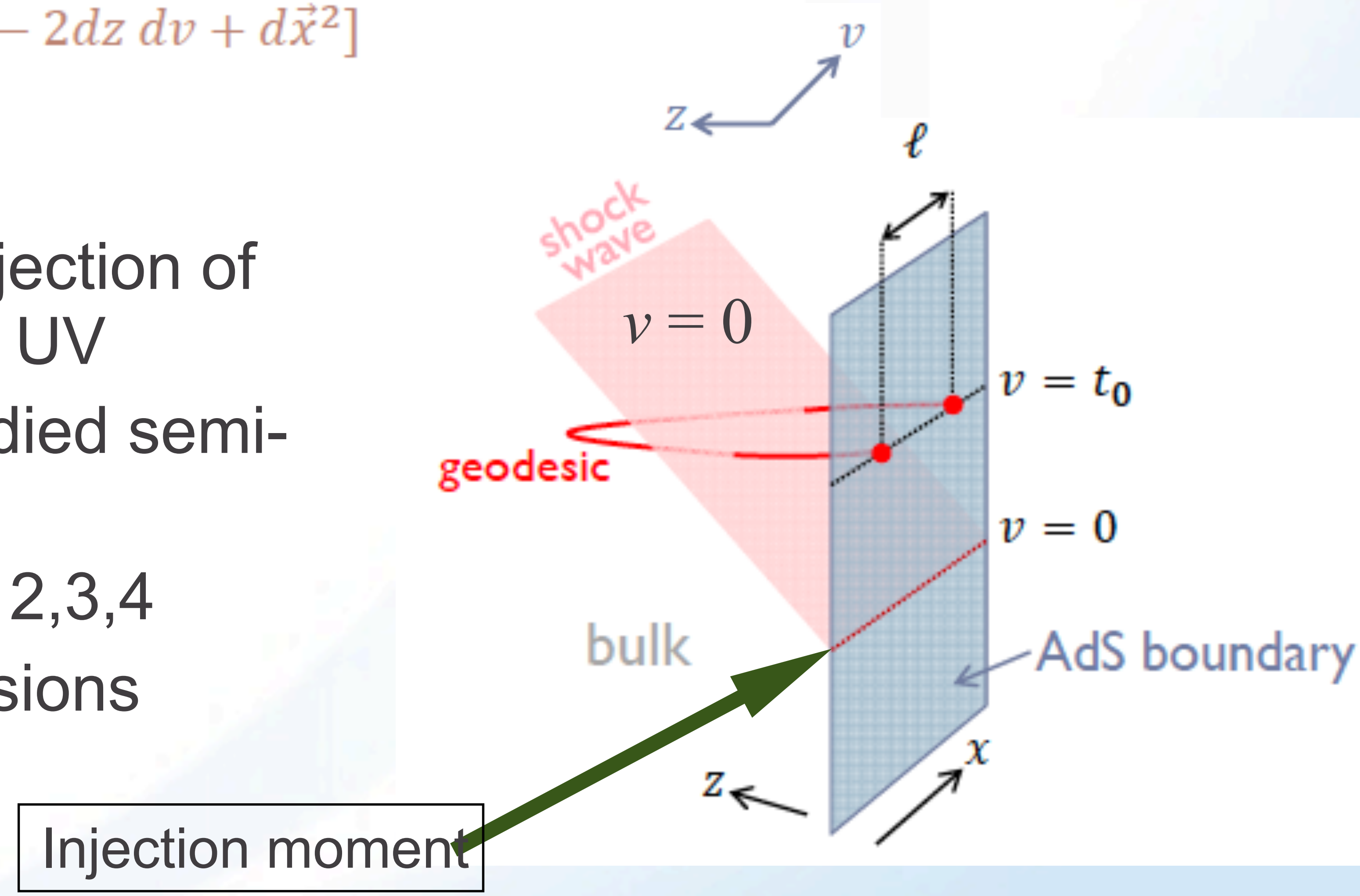
See also: S. Caron-Huot, P.M. Chesler & D. Teaney, arXiv:1102.1073

Vaidya-AdS geometry

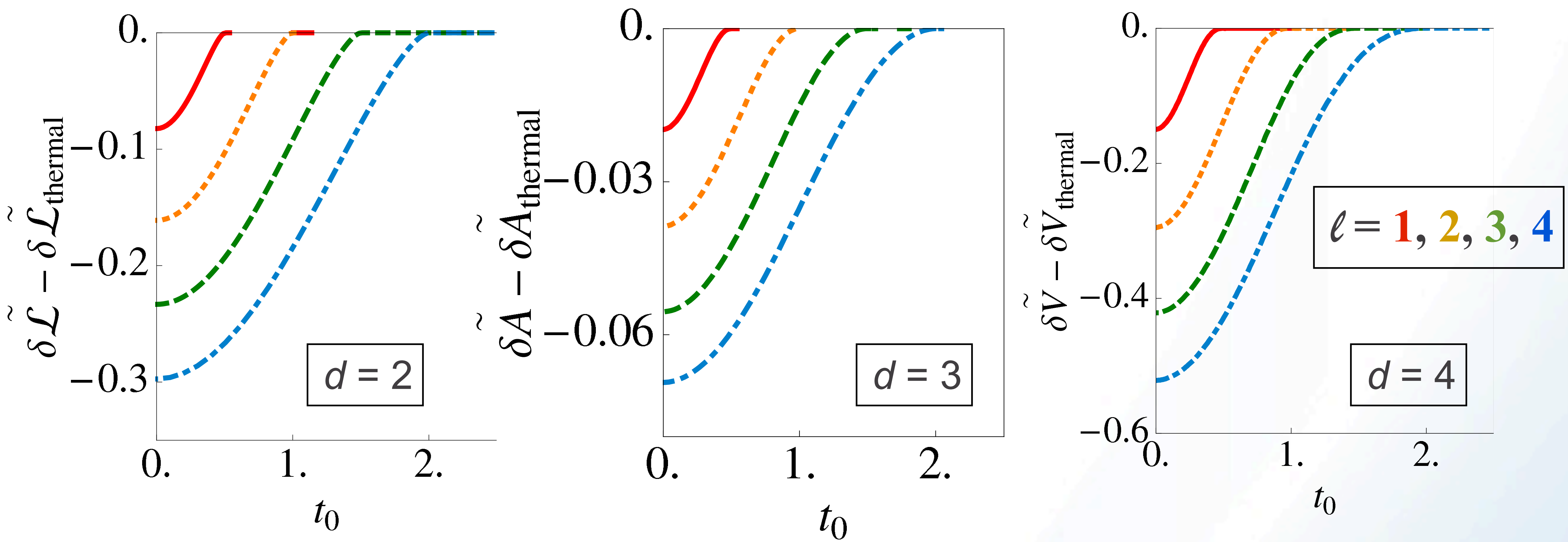
- Light-like (null) infalling energy shell in AdS (shock wave in bulk)
  - *Vaidya-AdS space-time* (analytical)

$$ds^2 = \frac{1}{z^2}\left[-\left(1 - m(v)z^d\right)dv^2 - 2dz\,dv + d\vec{x}^2\right]$$

  - $z = 0$: UV $\qquad z = \infty$: IR
  - Homogeneous, sudden injection of entropy-free energy in the UV
  - Thin-shell limit can be studied semi-analytically
  - We studied AdS$_{d+1}$ for d = 2,3,4
  - ⇔ Field theory in *d* dimensions



Entanglement entropy



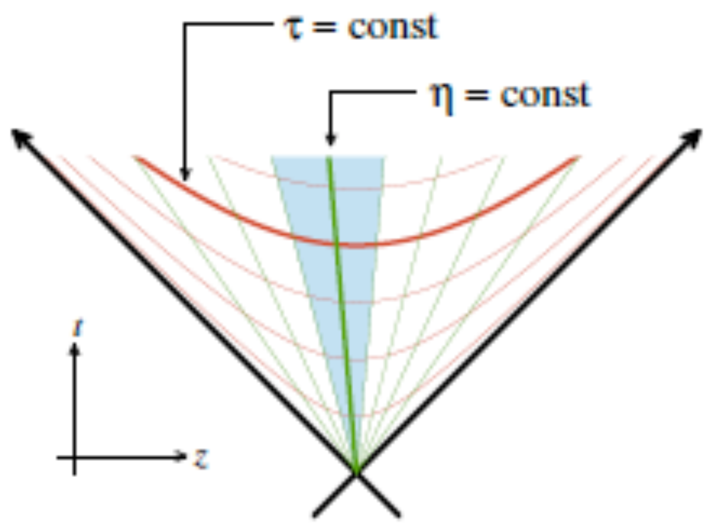
Thermalization time for entanglement entropy: $\tau_{\text{th}} = \ell/2$

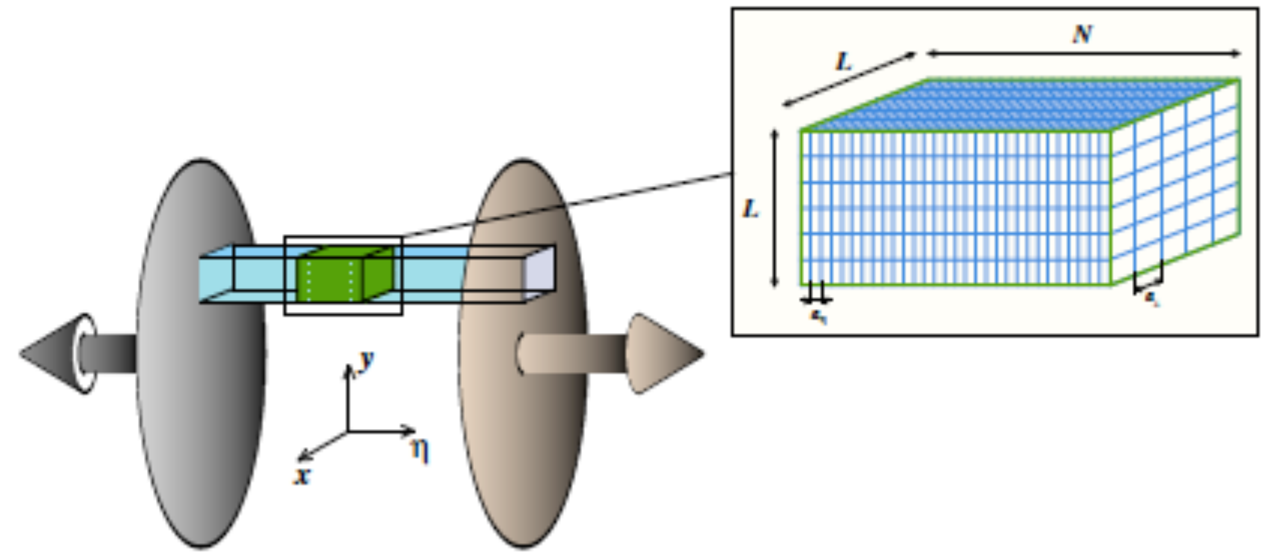
= time for light to escape from the center of the volume to the surface.

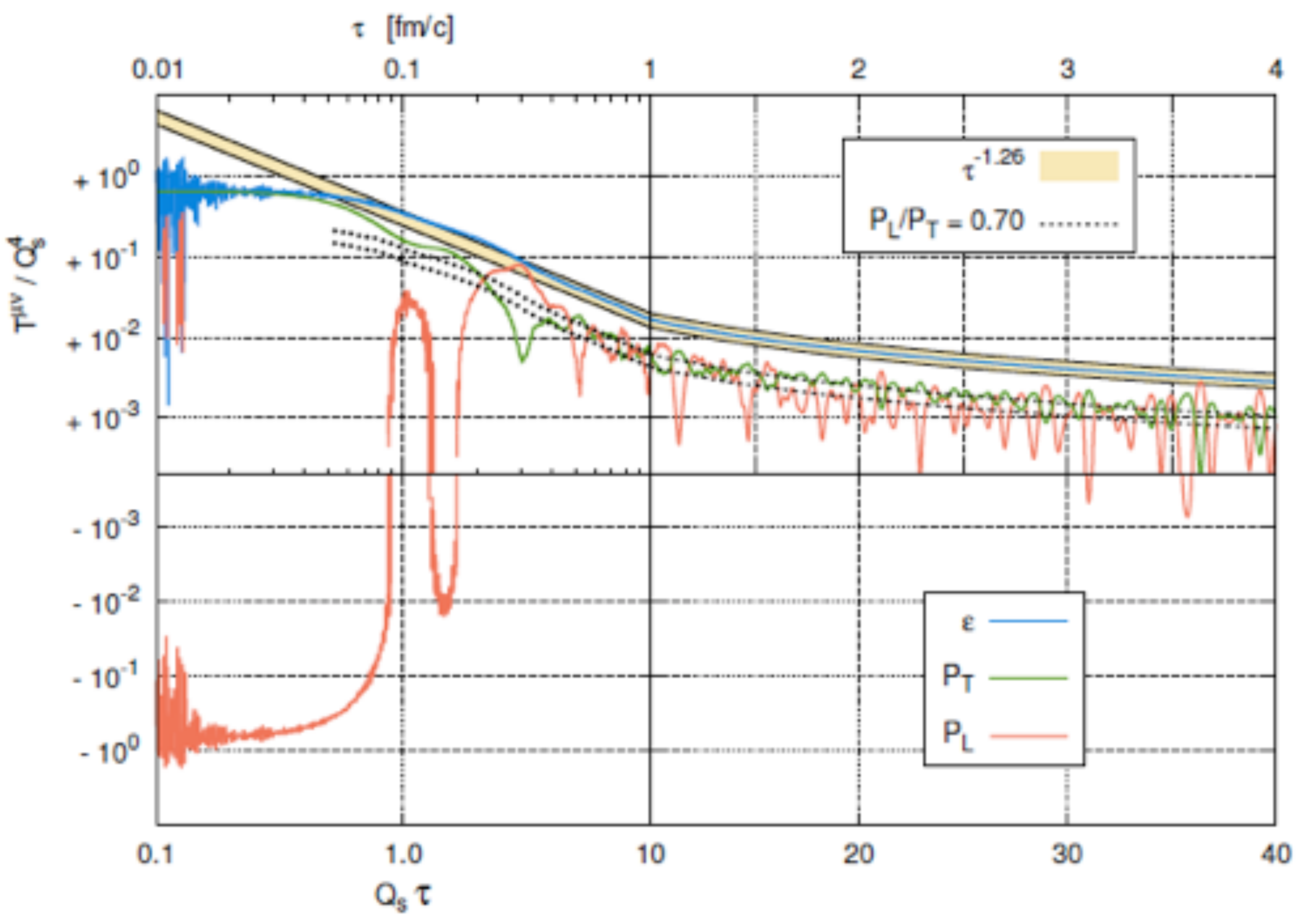
Other observables thermalize faster.

Crude estimate: $\tau_{\text{crit}} \sim 0.5\ \hbar/T \approx 0.3$ **fm/c for** $T = 300 - 400$ **MeV**

Glasma hydroization







T. Epelbaum & F. Gelis
arXiv: 1307.2214

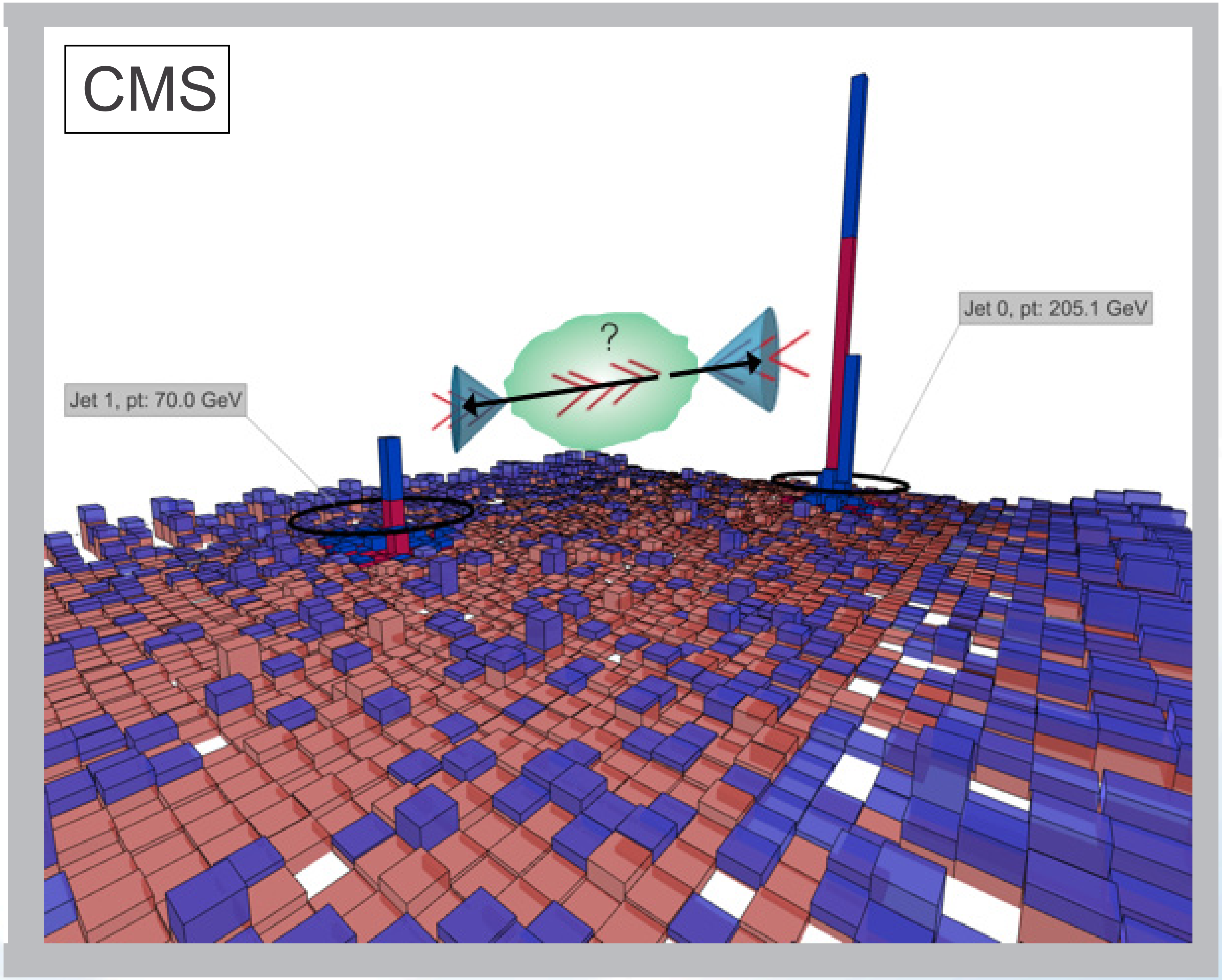
P_L/P_T = 0.70 after 0.4 fm/c !

Fit to: $\varepsilon(\tau) = \varepsilon_0 \, \tau^{-4/3} - 2 \, \eta_0 \, \tau^{-2}$

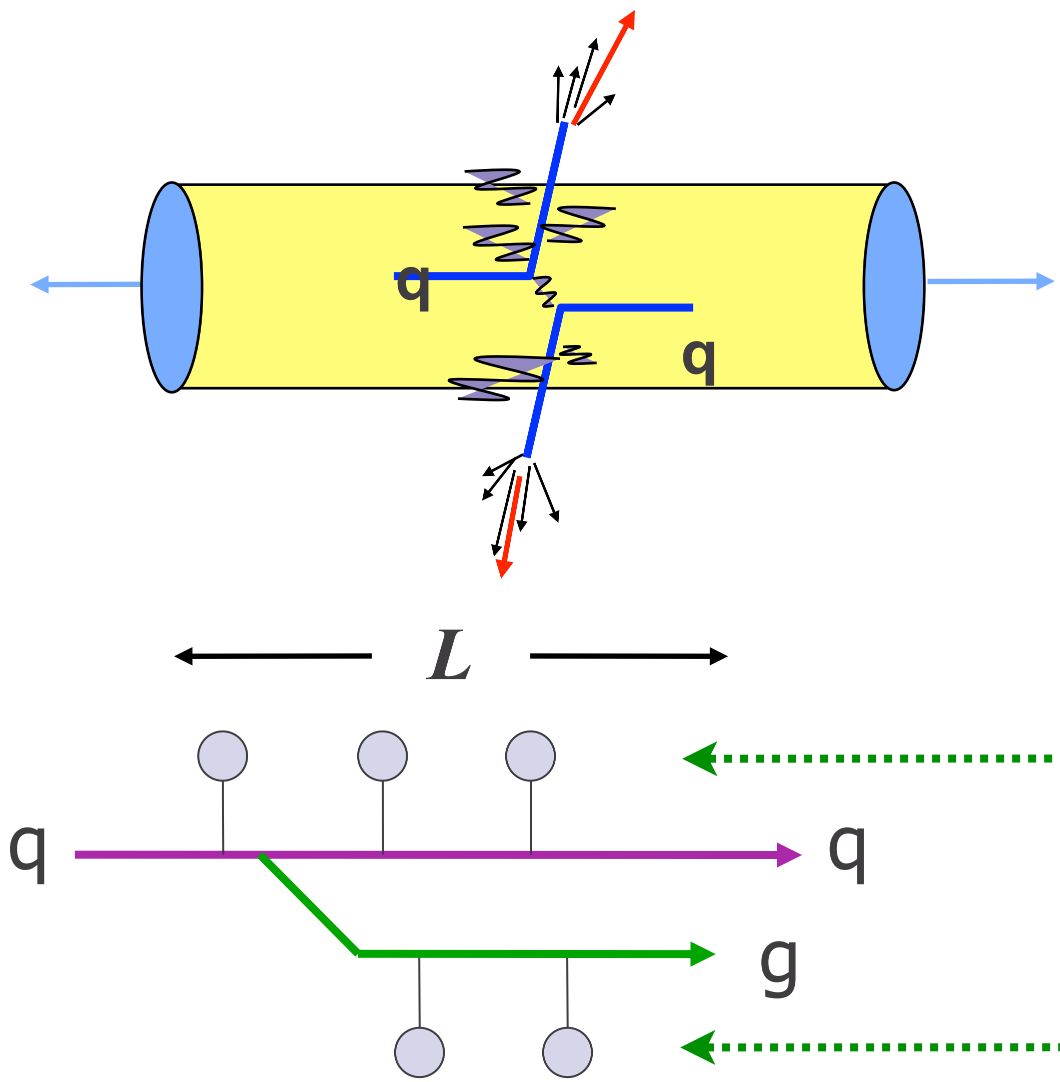
Consistent with $\eta/\varepsilon^{4/3} \approx 0.25$

Jet quenching

Di-jet asymmetry

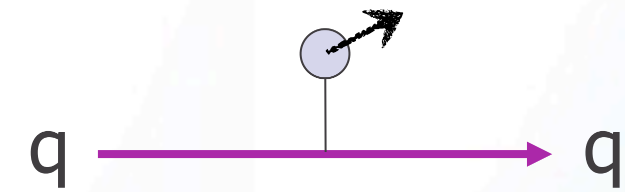


Parton energy loss



Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



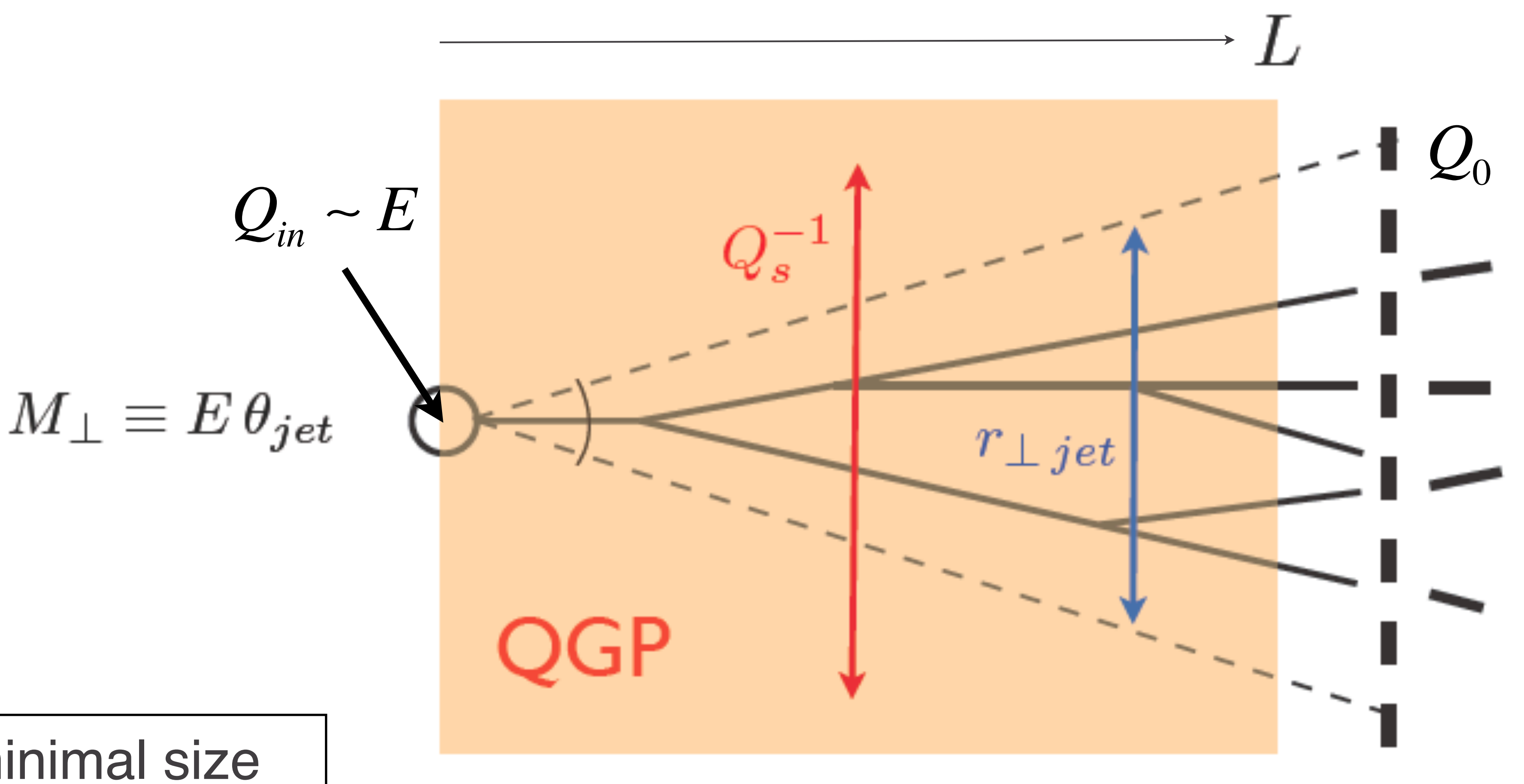
Radiative energy loss:

Scattering centers
$\Leftrightarrow$ color charges

$$\frac{dE}{dx} = -C_2\,\hat{q}\,L$$

$$\hat{q} = \rho \int q^2\, dq^2\, \frac{d\sigma}{dq^2} = \int dx^- \left\langle F_i^{+}(x^-) F^{+i}(0) \right\rangle$$

Jets in the medium



Q_s^{-1} = minimal size of probe to which the medium look opaque

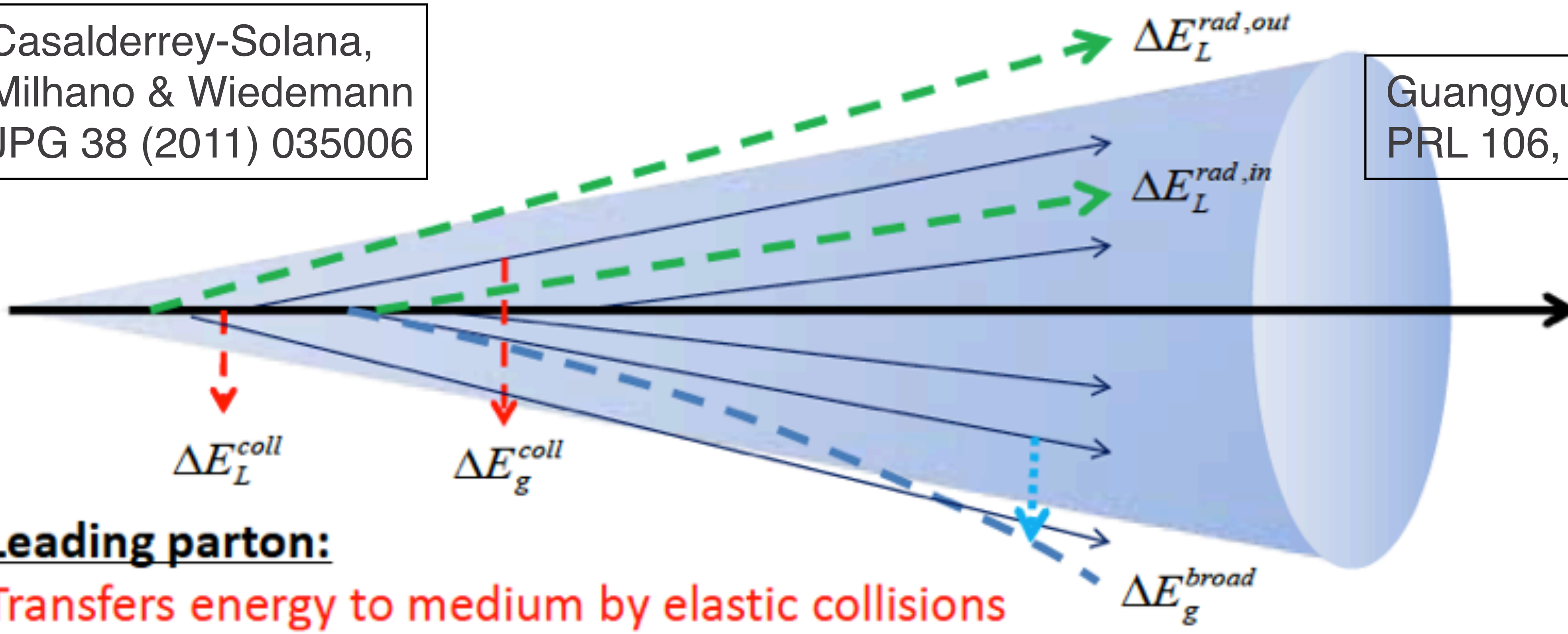
Momentum scale of medium $Q_s = \sqrt{qL} \approx m_D \sqrt{N_{\text{scatt}}}$

Transverse size of jet $r_{\perp\,\text{jet}} = \theta_{\text{jet}} L$

Jet collimation

Casalderrey-Solana,
Milhano & Wiedemann
JPG 38 (2011) 035006

Guangyou Qin & BM
PRL 106, 162302 (2011)



Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega,k_\perp^2,t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

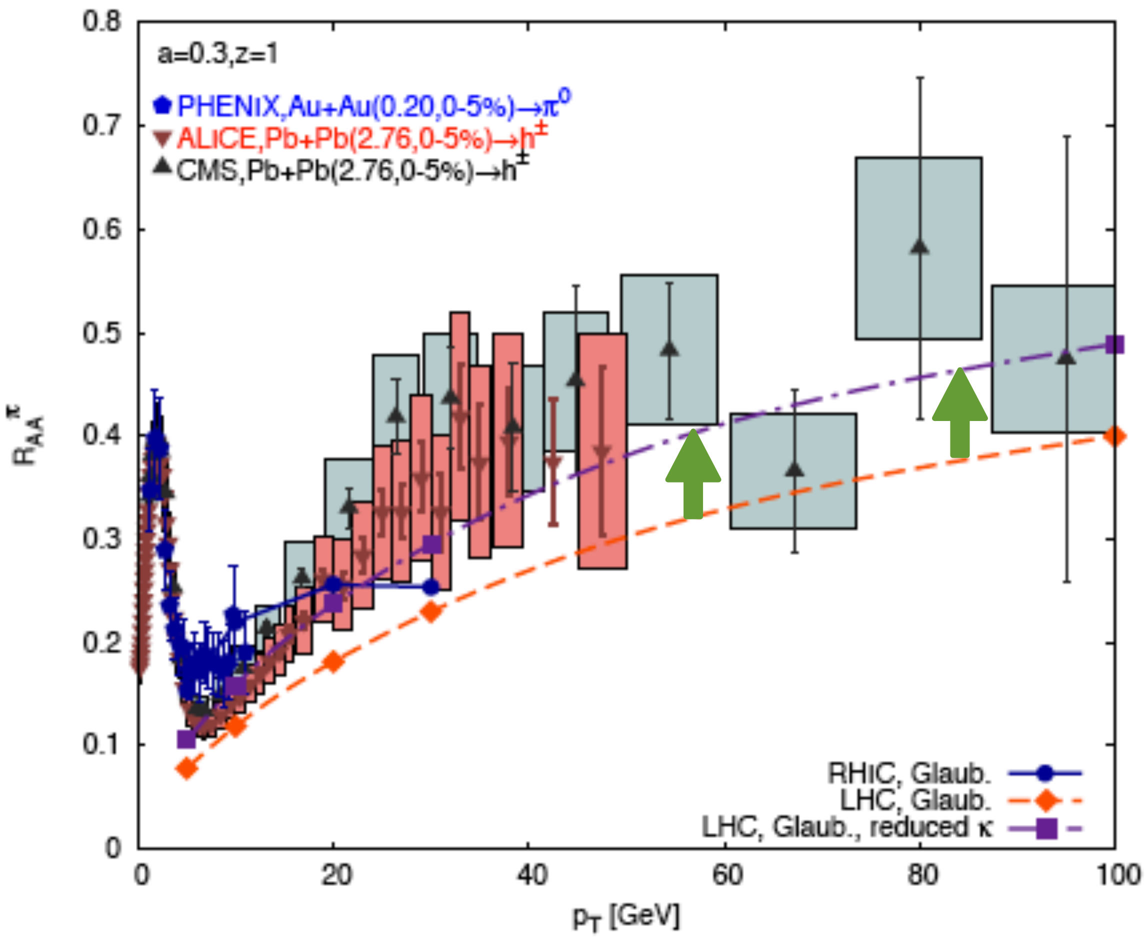
Core questions

- What is the mechanism of energy loss ?
  - “radiative” = into non-thermal gluon modes
  - “collisional” = directly into thermal plasma modes
- How are radiative and collisional energy loss affected by the structure of the medium (quasiparticles or not)?
  - Quasiparticle masses in weak coupling
  - AdS/CFT inspired models with weak-strong coupling transition?
- What happens to the lost energy and momentum ?
  - If “radiative”, how quickly does it thermalize = what is its longitudinal momentum (z) distribution ?
  - What is its angular distribution (the jet “shape”) = how much is found in a cone of angular size R ?
- How do the answers depend on the parton flavor ?

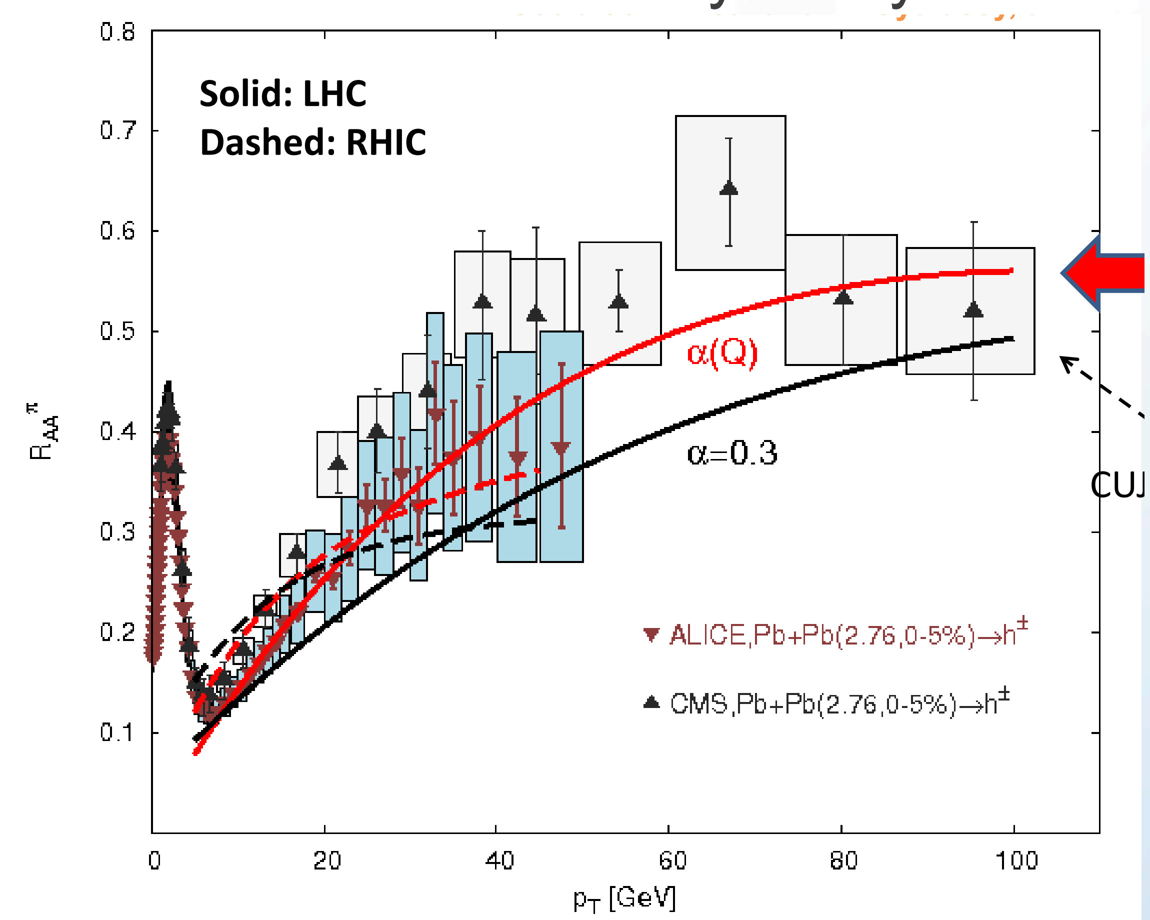
Color opacity

$\kappa \sim \alpha_s \hat{q} \sim \alpha_s^3$ $\kappa_{LHC} \approx 0.6\ \kappa_{RHIC}$ α_s runs!

Betz & Gyulassy, arXiv:1201.0281



Buzzatti & Gyulassy



Is T-dependence of q^ gradual or rather a steep change for T > T_c ?

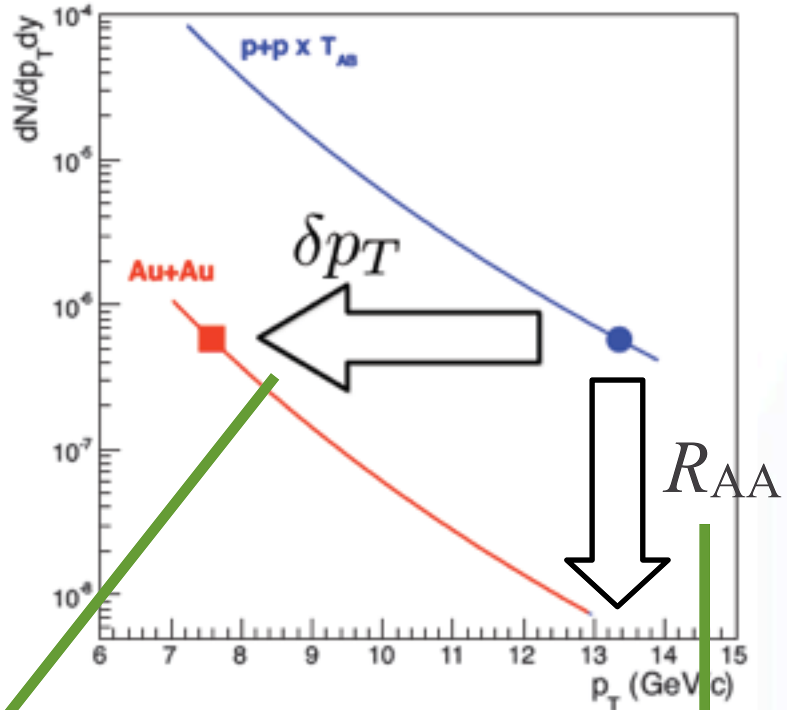
Hadron R_{AA}

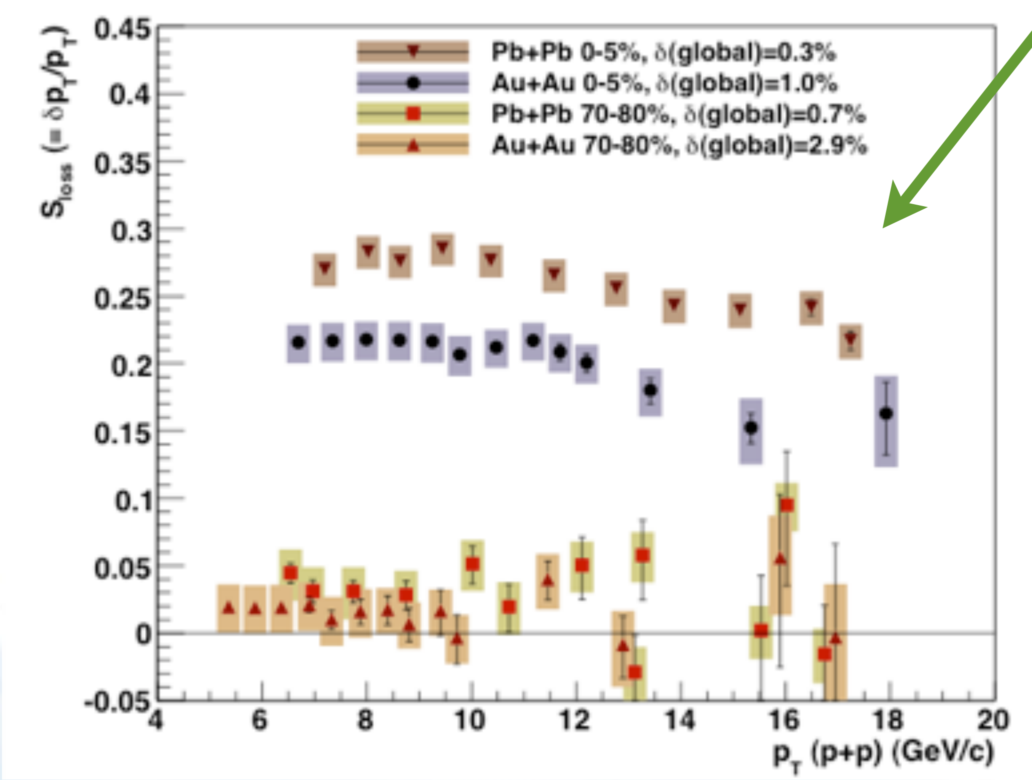
$(\delta p_T)_{\mathrm{LHC}} \approx 1.3\ (\delta p_T)_{\mathrm{RHIC}}$

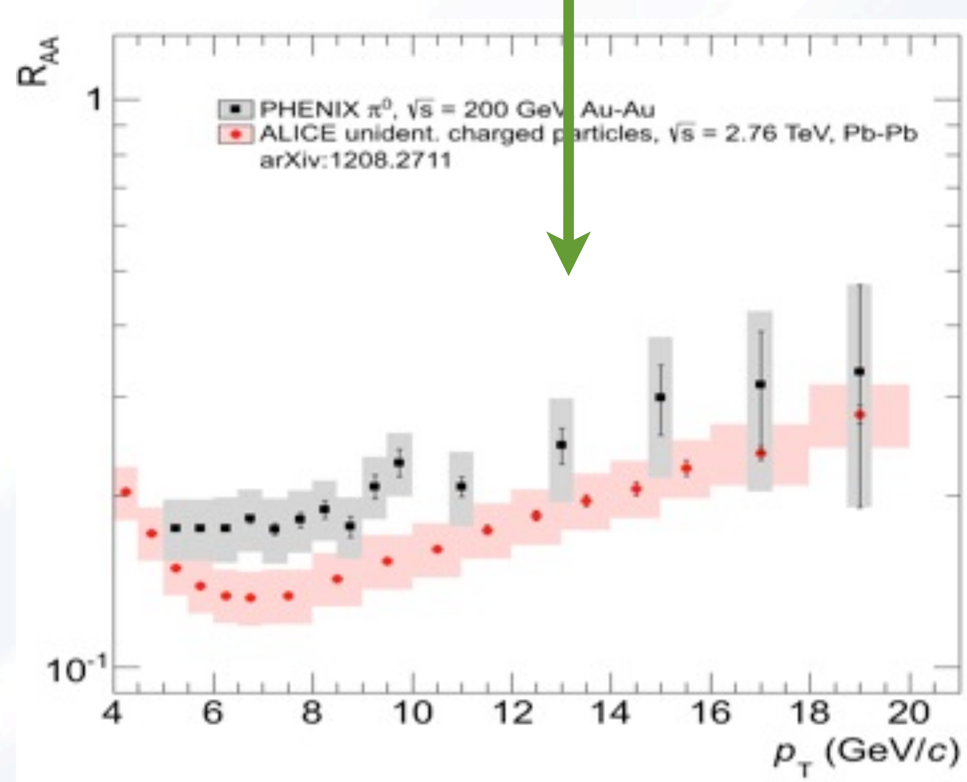
but:

$(dN/dy)_{\mathrm{LHC}} \approx 2.2\ (dN/dy)_{\mathrm{RHIC}}$

$\Rightarrow$ QGP at LHC is less opaque to hard partons

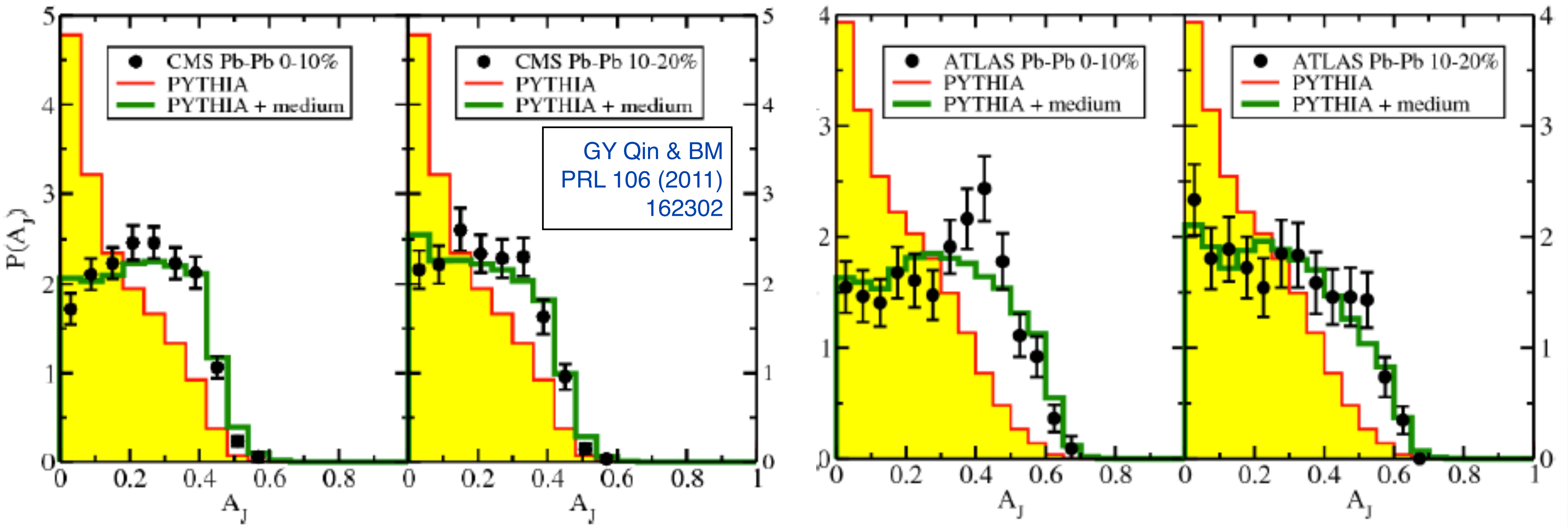






Di-jet asymmetry

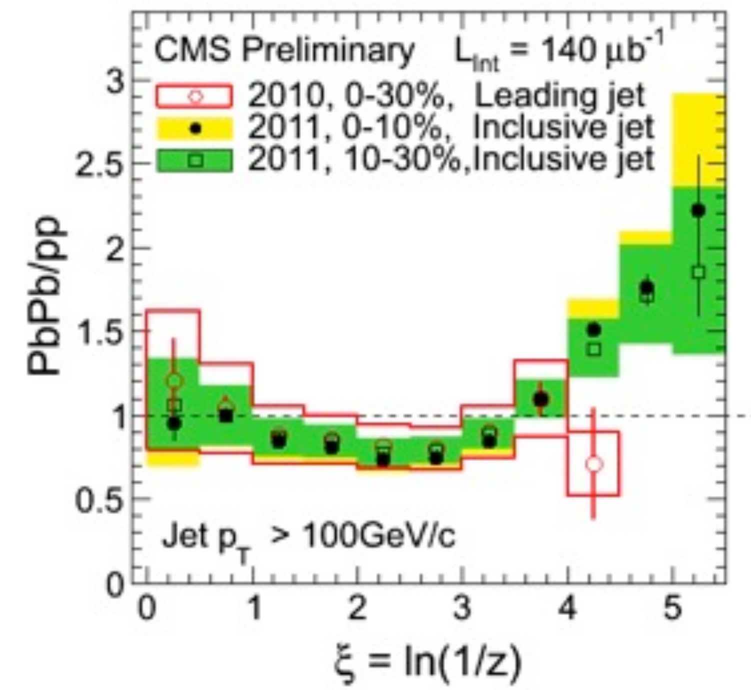
CMS data　　　　　　　　　　ATLAS data

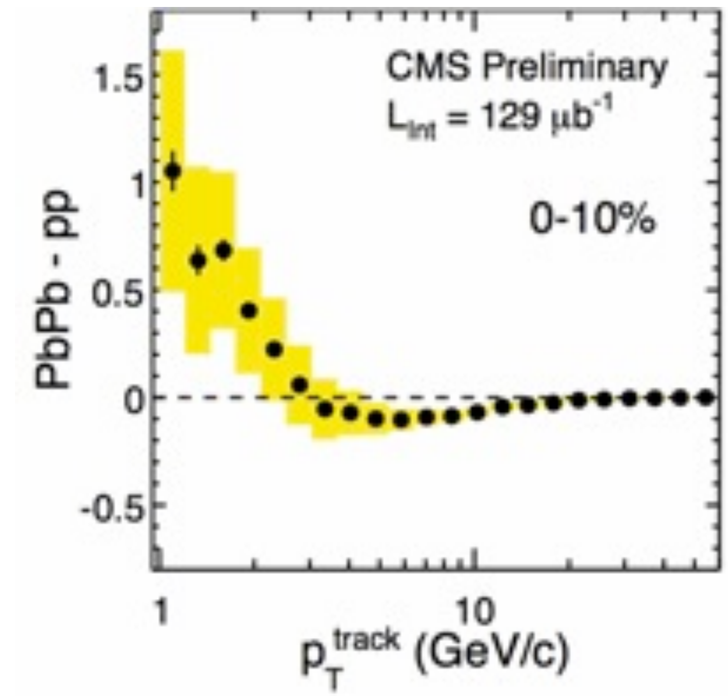


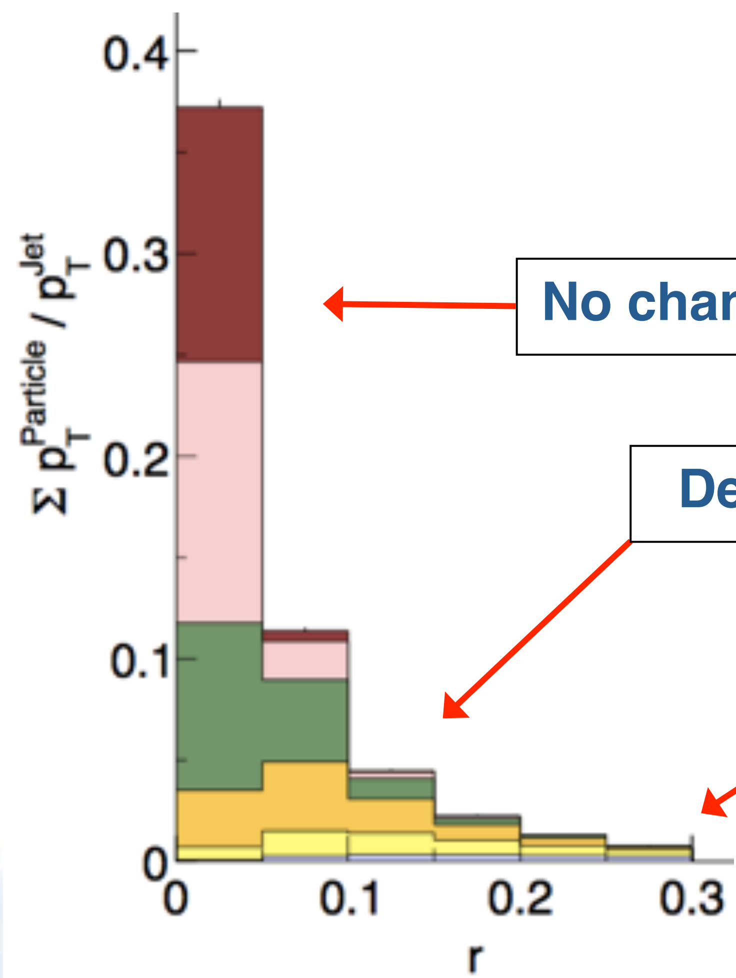
ATLAS and CMS data differ in cuts on jet energy, cone angle, etc; results depend somewhat on precise cuts and background corrections. Several calculations using pQCD jet quenching formalism fit the data.

General conclusion: *pQCD jet quenching can explain these data.*

Jet modification synopsis



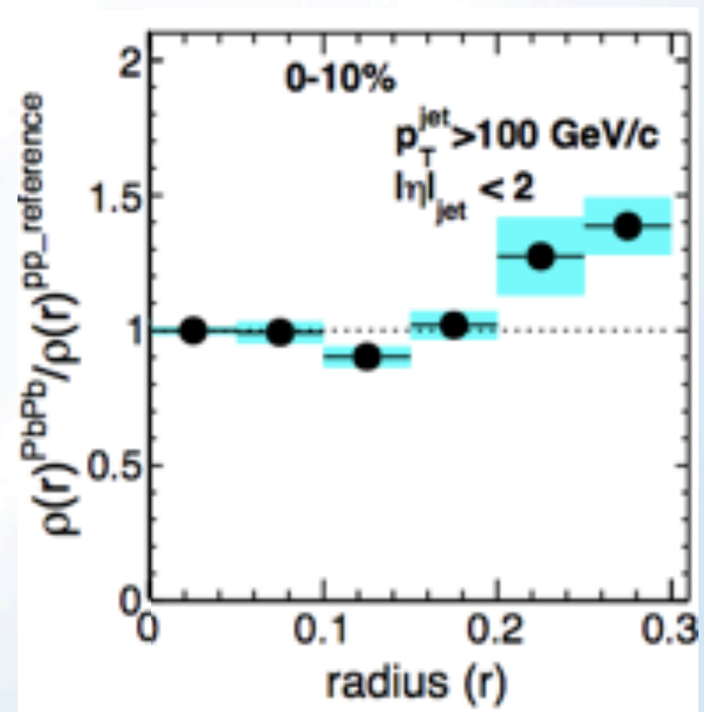




No change at small r, high p_T

Depletion at intermediate r, p_T

Excess at large r, low p_T



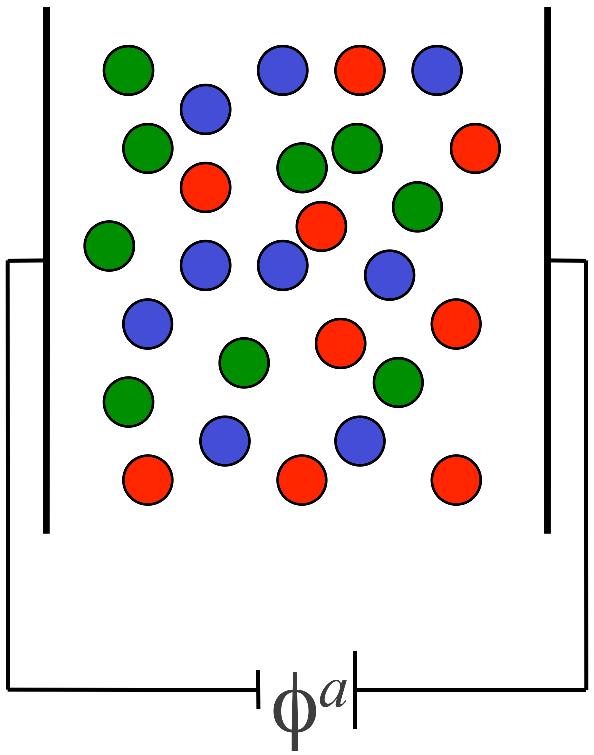
Jets summary

- Strongly coupled (AdS/CFT) jets are ruled out by LHC data:
  - Partons with p_T > 10 GeV/c are not strongly coupled, but behave as quasiparticles.
  - pQCD jet quenching theory works for high-p_T jets, R_{AA}.
- Jet modification is concentrated at pT < 4 GeV/c and large angles in the jet cone:
  - Gluons with $p_T \leq$ few GeV/c may be strongly coupled.
- Relation between medium and jet scales different at RHIC and LHC:
  - Need for a large acceptance, calorimetric jet detector at RHIC: sPHENIX.

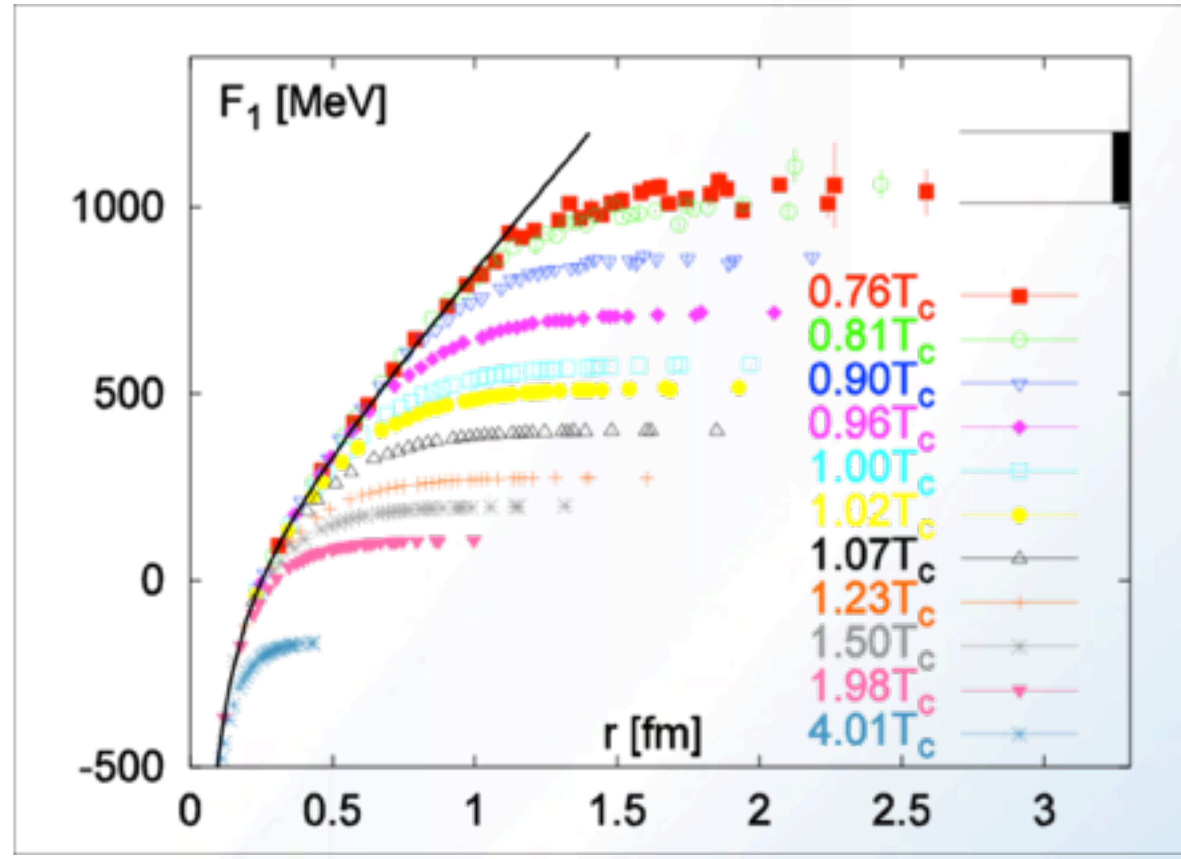
Quarkonium melting

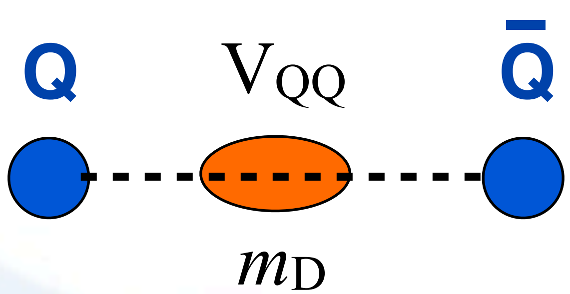
In the good old days...

... life seemed simple: It's all color screening



Lattice QCD





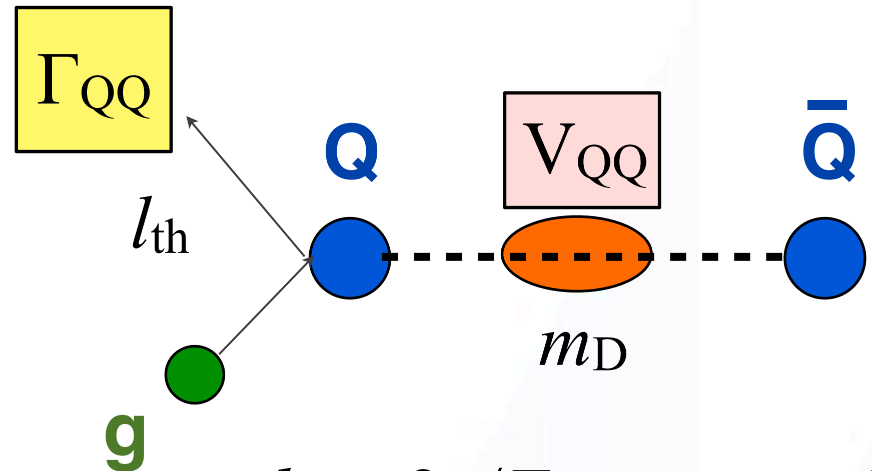
$m_D \sim gT$

Only the data did not quite fit the theory!

The real story...

...is more complicated (as usual).

Q-Qbar bound state interacts with medium elastically and inelastically!

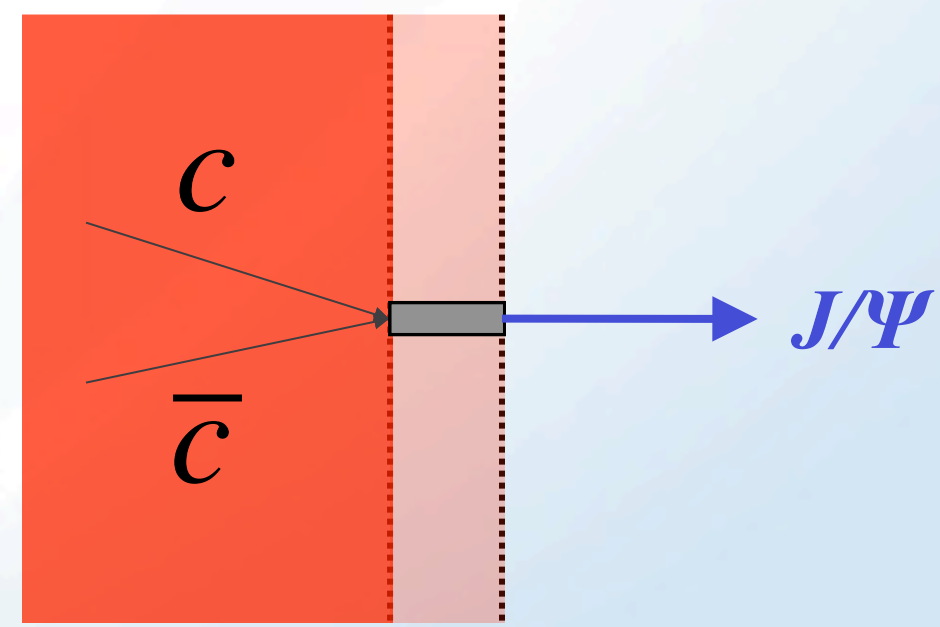


$$l_{th} \sim 2\pi/T, \qquad m_D \sim gT$$

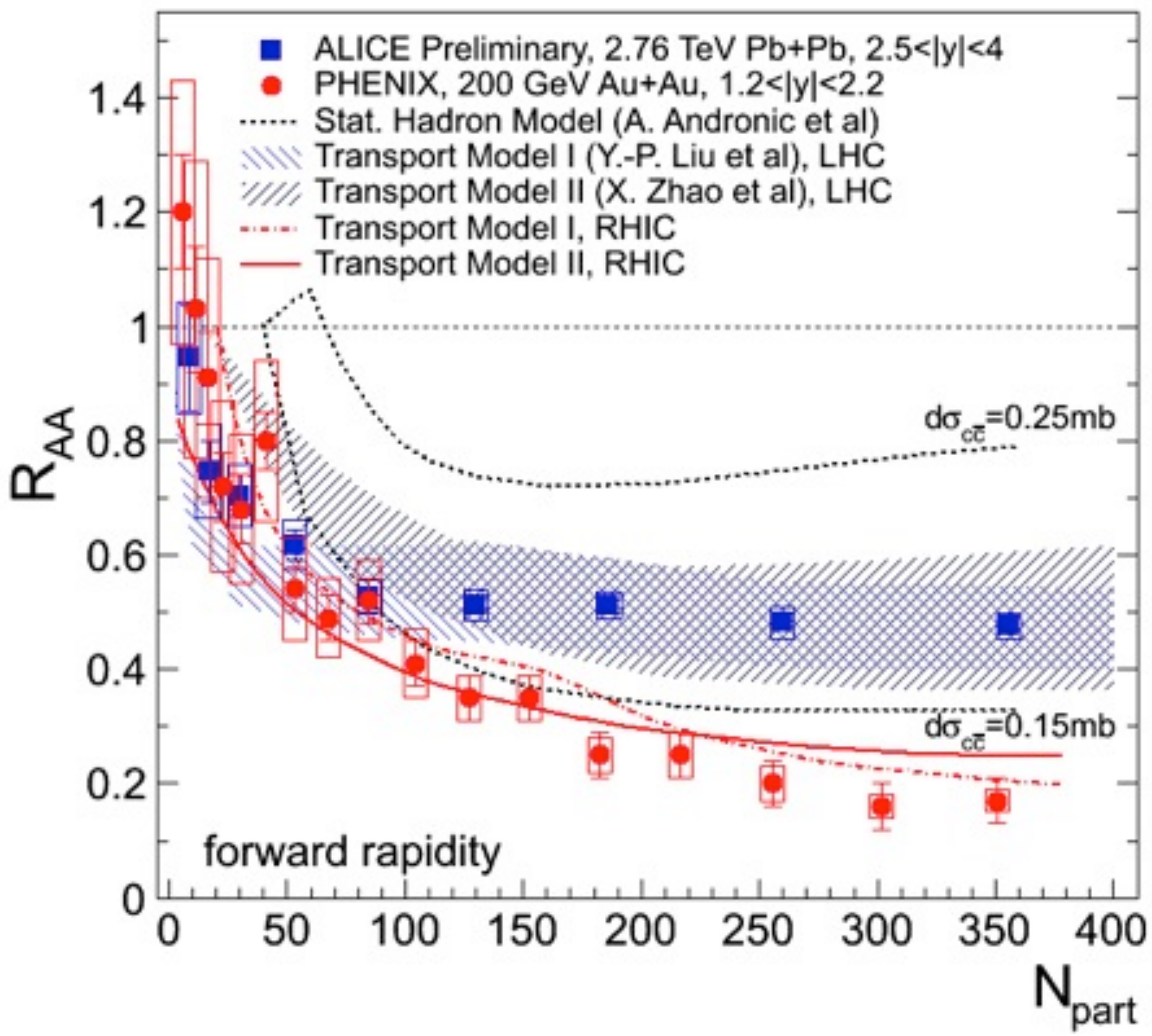
$$i\hbar \frac{\partial}{\partial t}\Psi_{Q\bar{Q}} = \left[\frac{p_Q^2 + p_{\bar{Q}}^2}{2M} + V_{Q\bar{Q}} - \frac{i}{2}\Gamma_{Q\bar{Q}} + \eta \right] \Psi_{Q\bar{Q}}$$

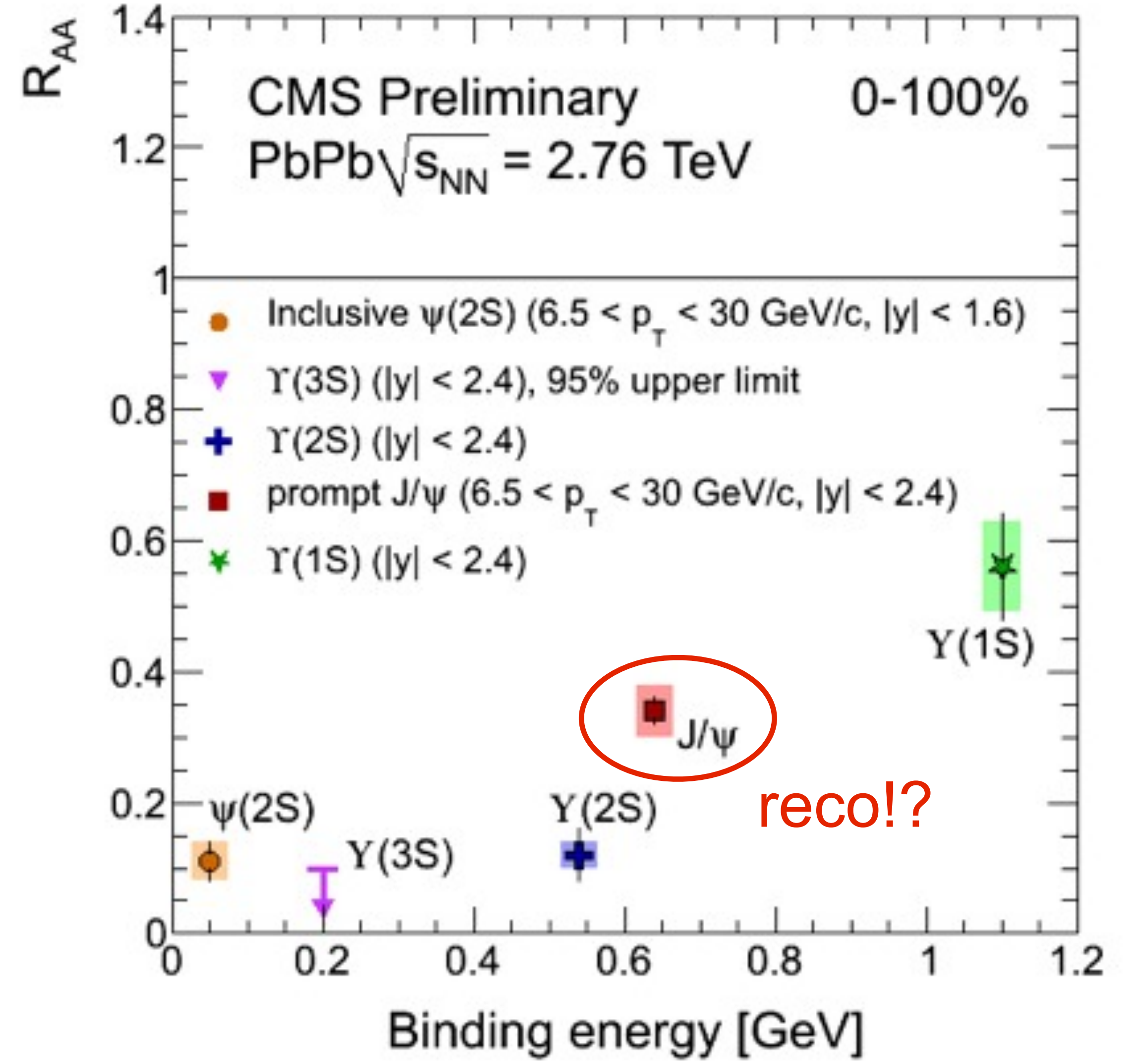
Heavy-Q energy loss and Q-Qbar suppression are closely related

Recombination can also contribute when c-quark density is high enough!



J/ψ suppression





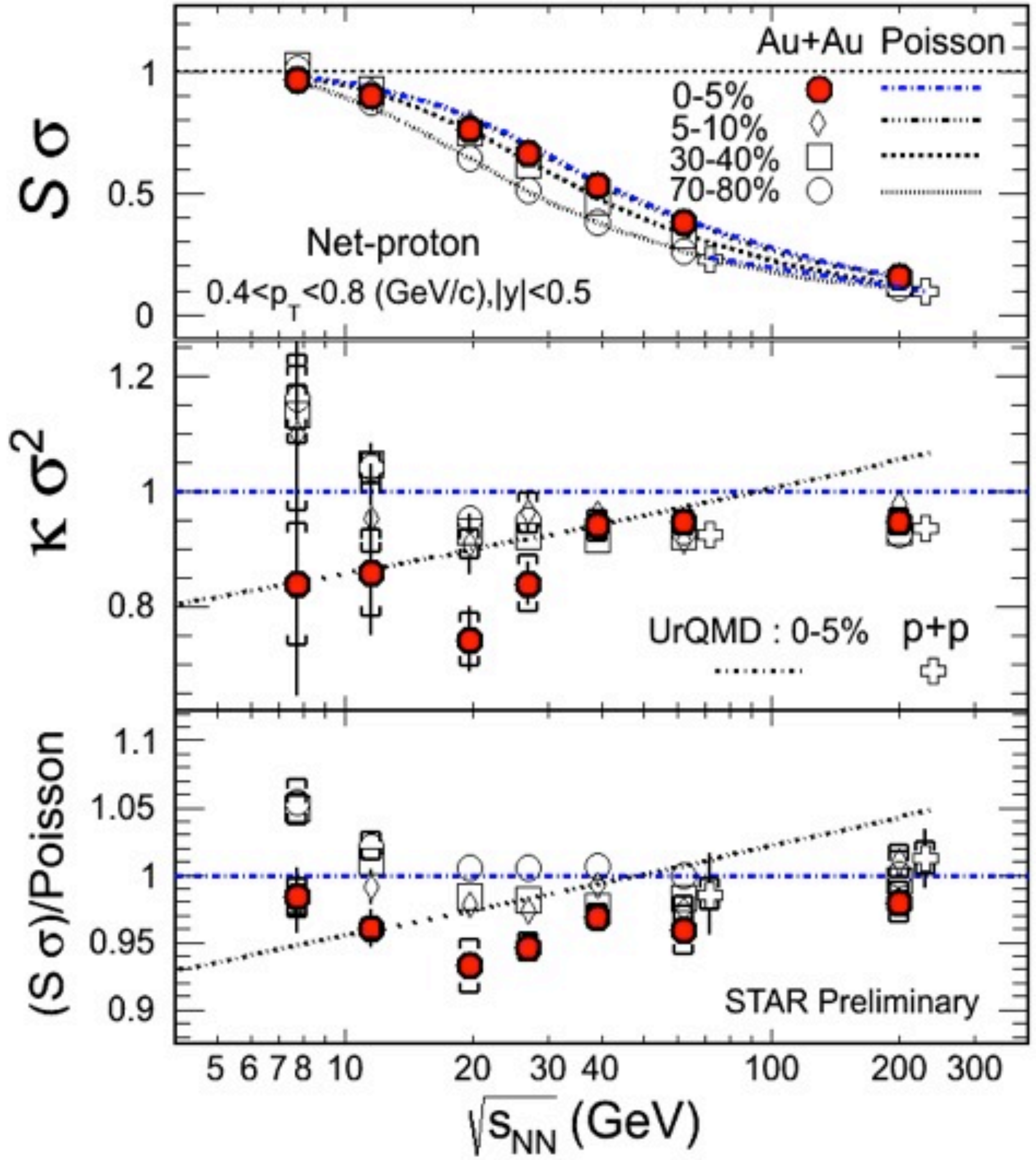
Less J/ψ suppression at LHC than at RHIC, at mid-rapidity and mid-forward rapidities:
c-cbar recombination explains data.

Full range of quarkonium states is becoming accessible.

Toward a cooler, denser QGP

Beam energy scan I

- BES Phase 1 analyses near final
  - Results presented at QM 2012
  - First publication, PR C 86 (2012) 54908
- Hints of exciting behavior, but higher luminosity Phase 2 necessary for definitive results
- Run at 15 GeV planned for 2014

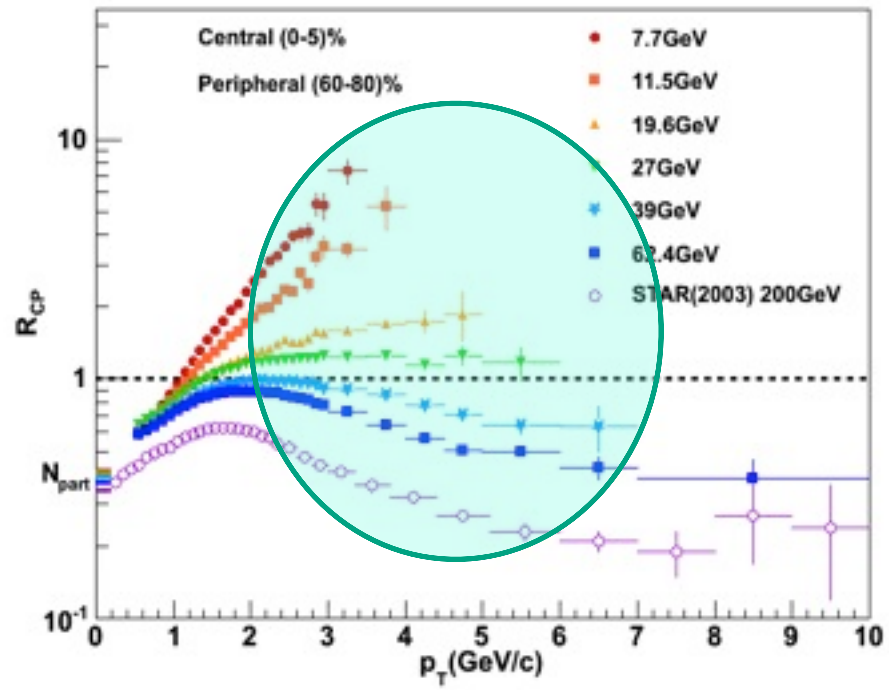


Data taken at
$\sqrt{s_{NN}}$ = 39, 27, 19.6, 11.5, 7.7 GeV

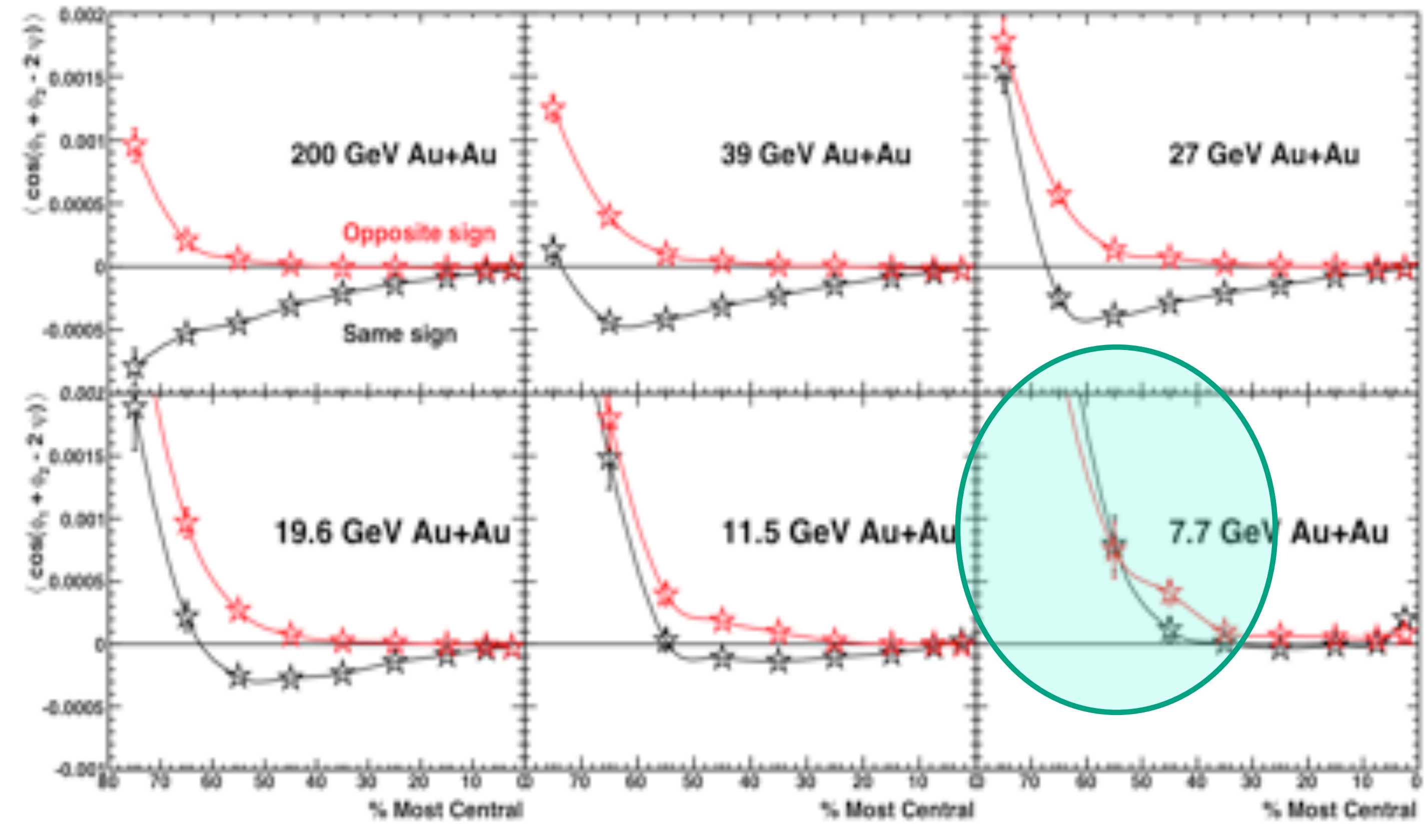
Partonic interaction dominant
at $\sqrt{s_{NN}} \geq$ 39 GeV
Hadronic interaction dominant
at $\sqrt{s_{NN}} \leq$ 11.5 GeV

Where is the end of the sQGP?

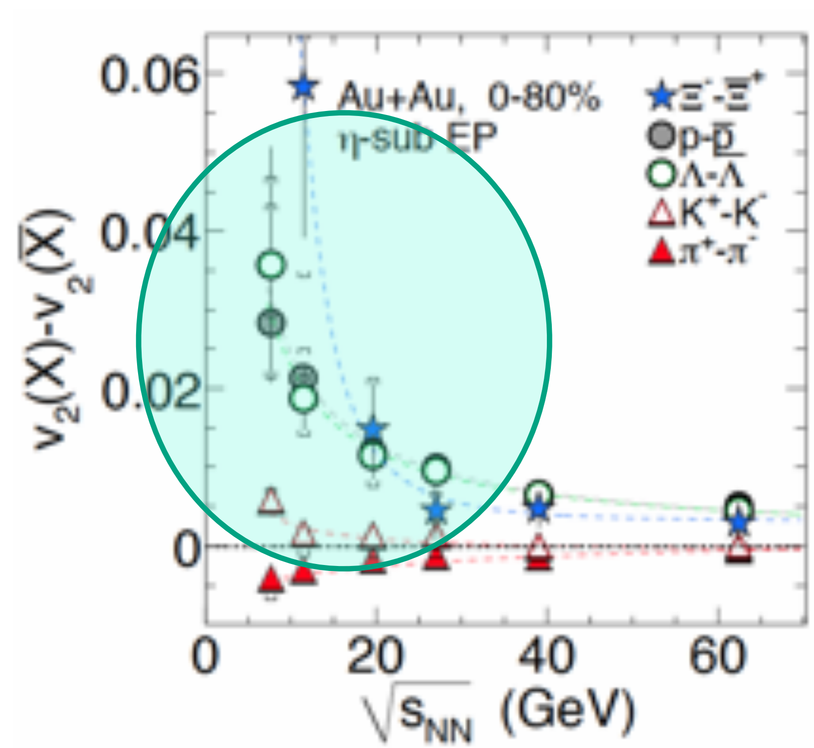
Jet-quenching



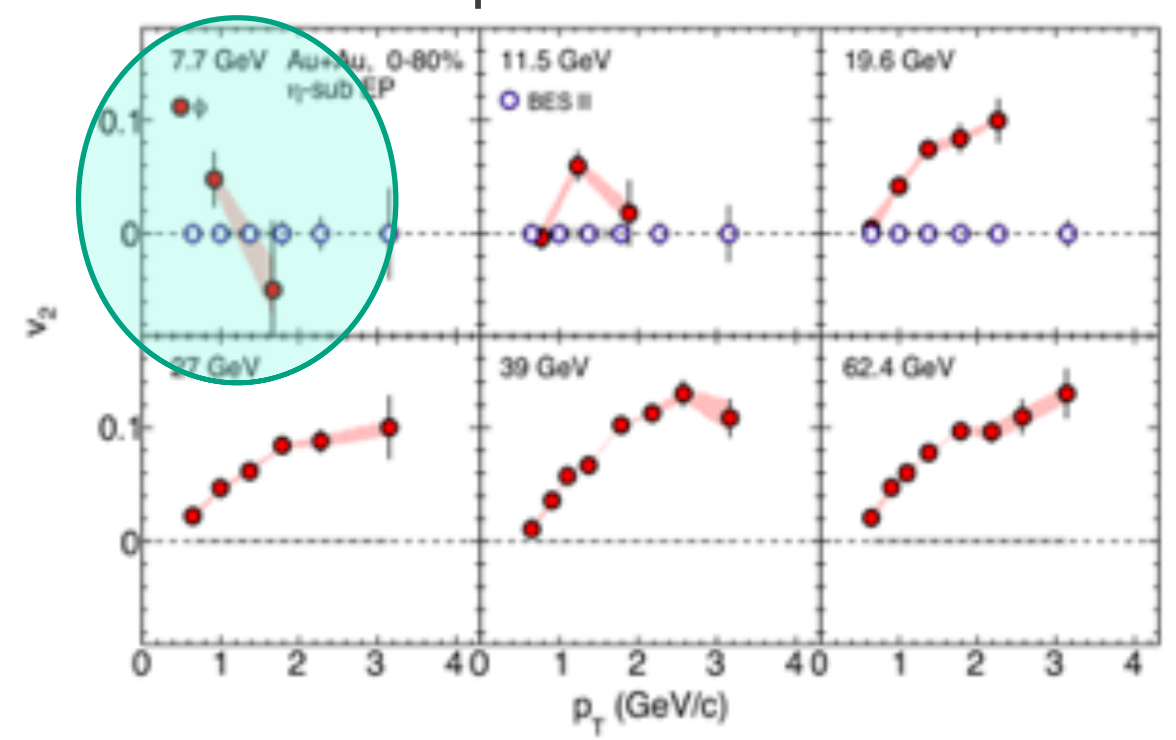
"Local Parity Violation"



NQ Scaling in v_2



ϕ-meson flow

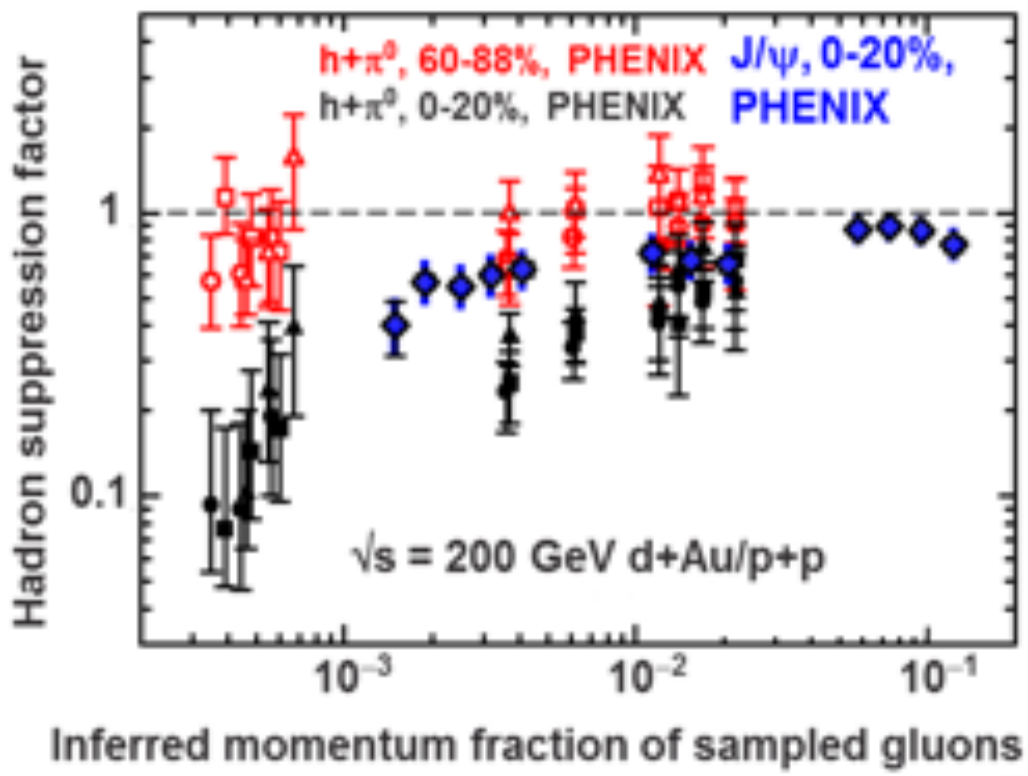


Cold Nuclear Matter ?

d+Au probes cold nuclei

Idea: Difference between p+p and d+Au can be interpreted as low-x parton saturation in Au.

Can low-order higher twist effects be excluded as explanation?



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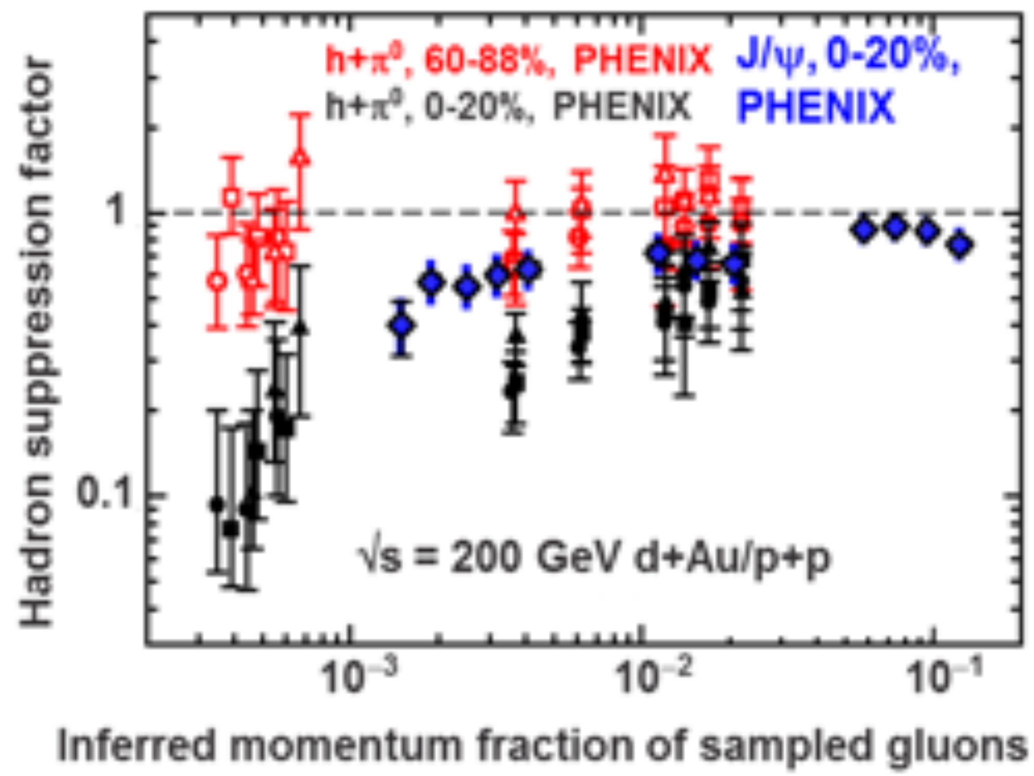
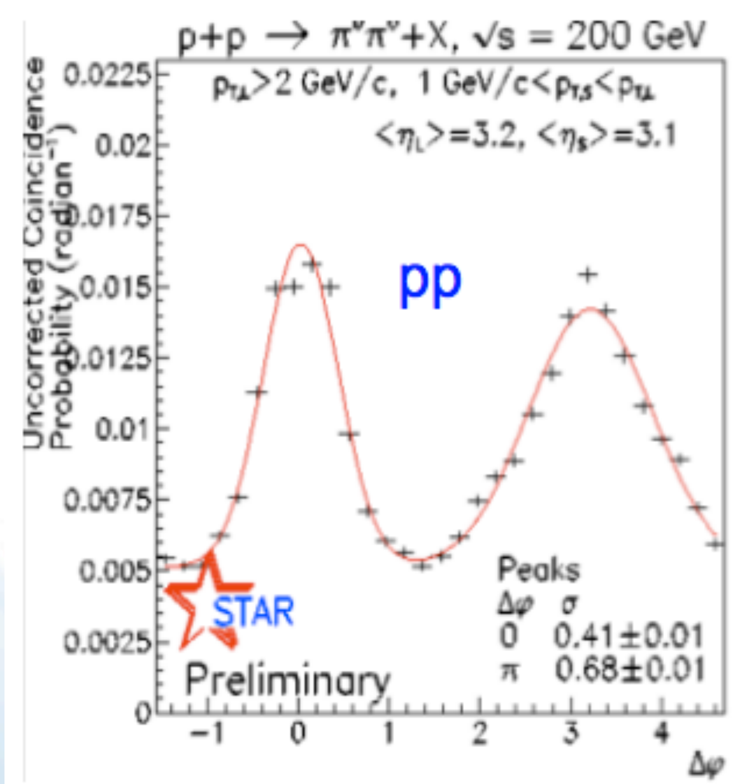
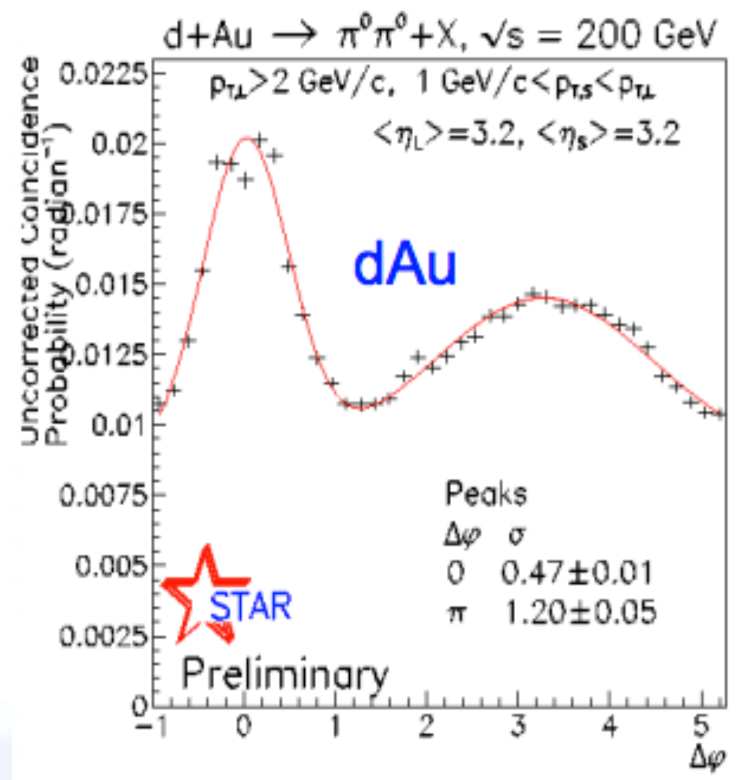


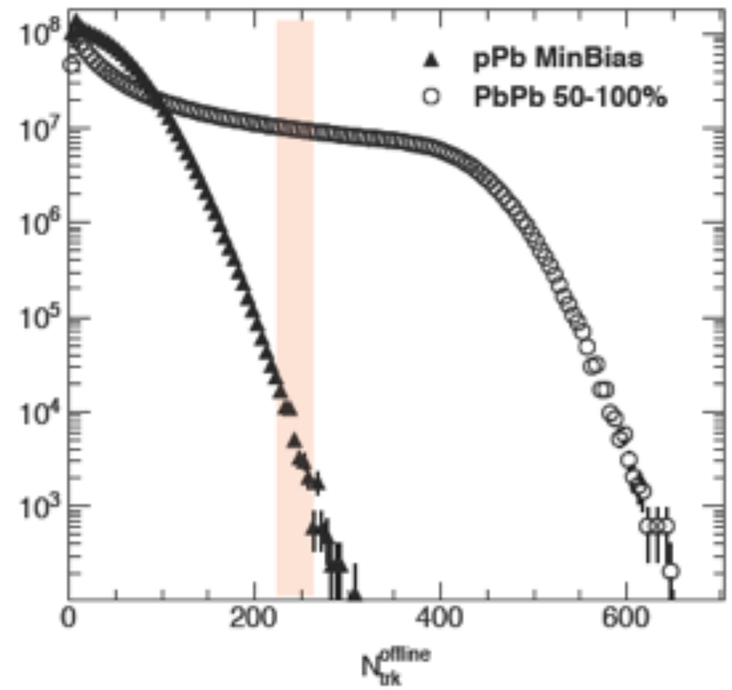


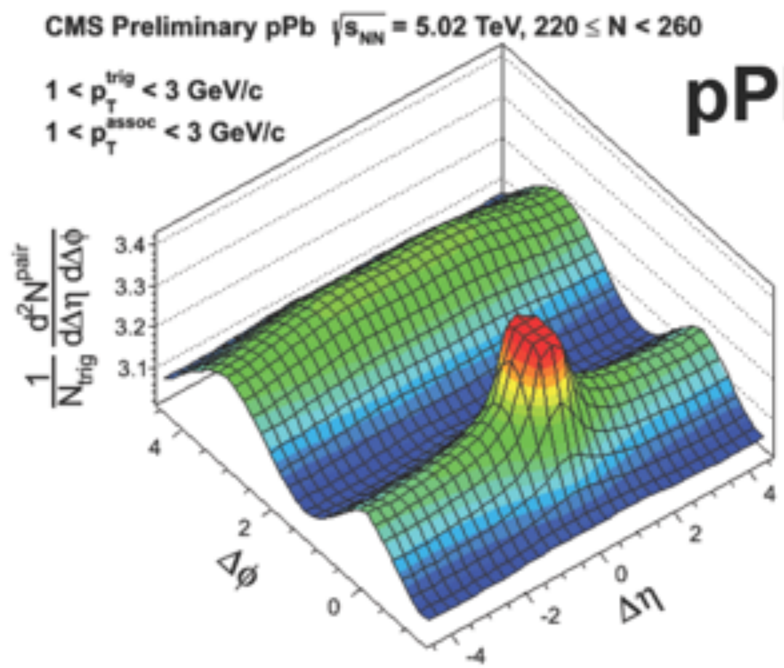


Probing saturation:

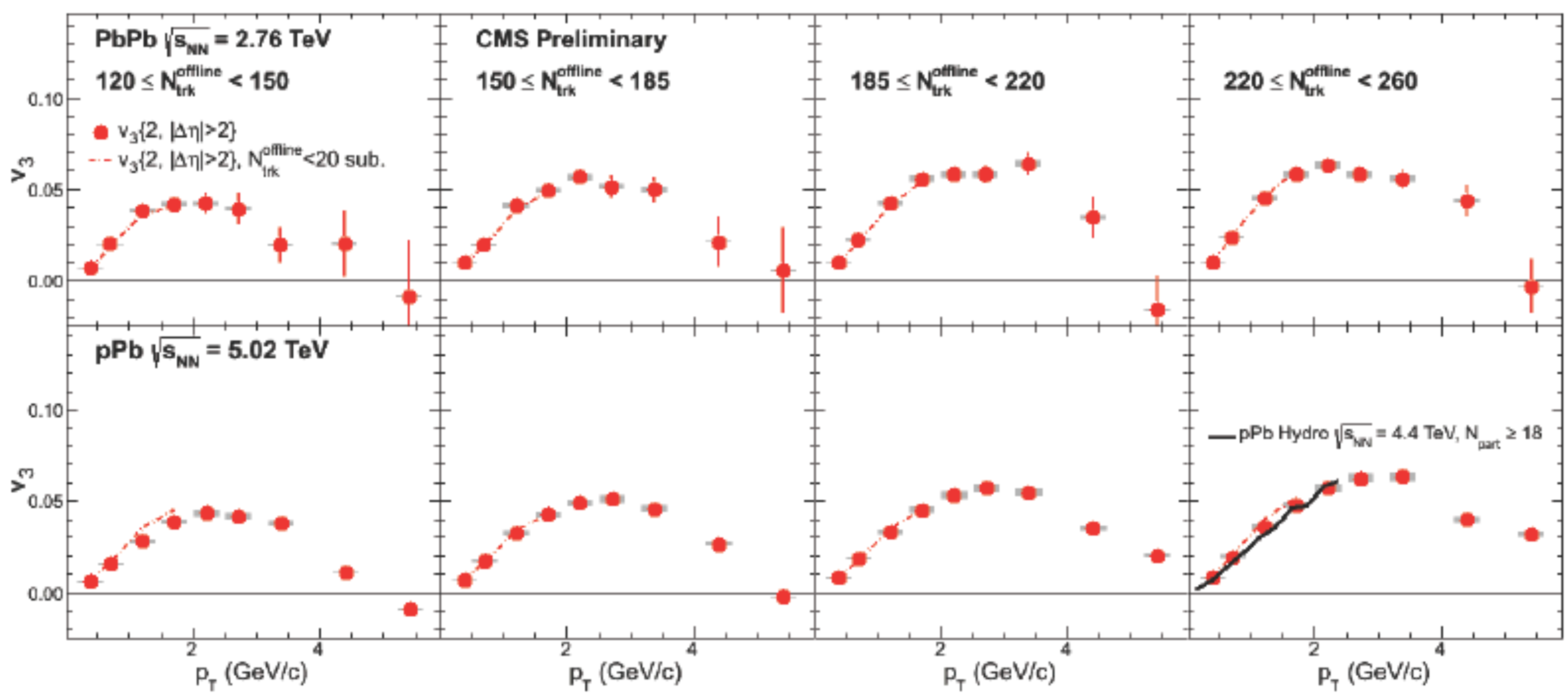
Away side broadening of $\pi\pi$ correlations is consistent with CGC expectations.

QGP in p+A ?





pPb



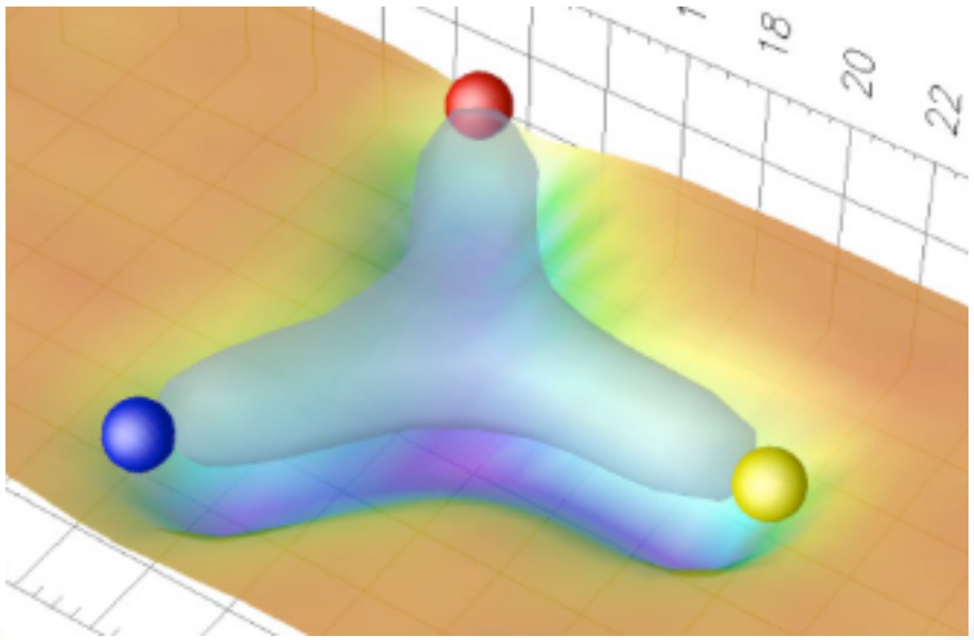
PbPb

pPb

“Fat” Protons

As any quantum state, protons fluctuate in size and shape. When a proton is small, one speaks of color transparency. But sometimes a proton can be large. What does such a “fat” proton look like?

The “stringy” proton



F. Bissey et al., PRD76, 114512

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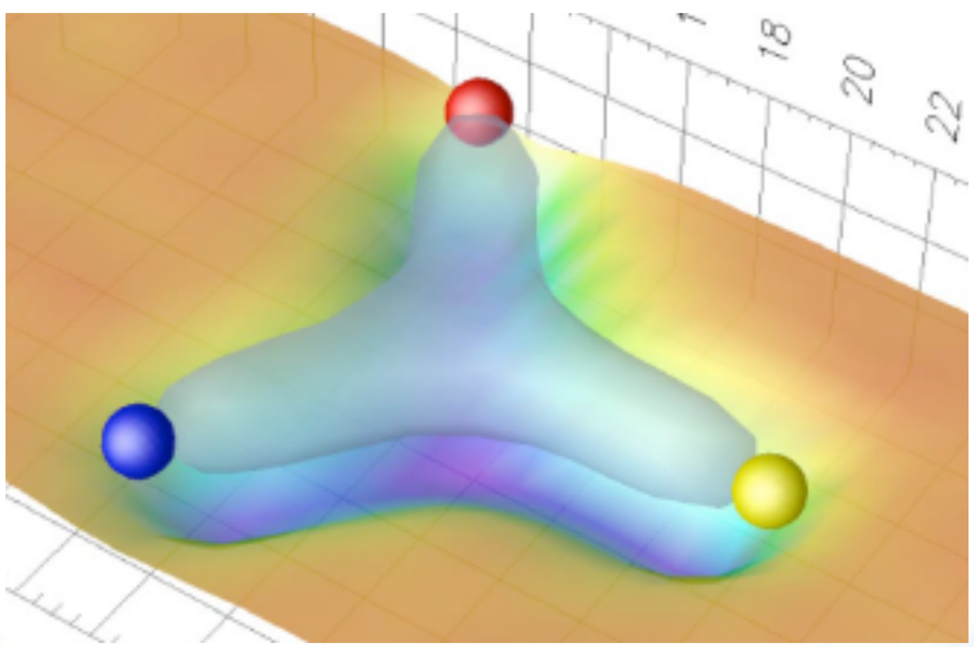
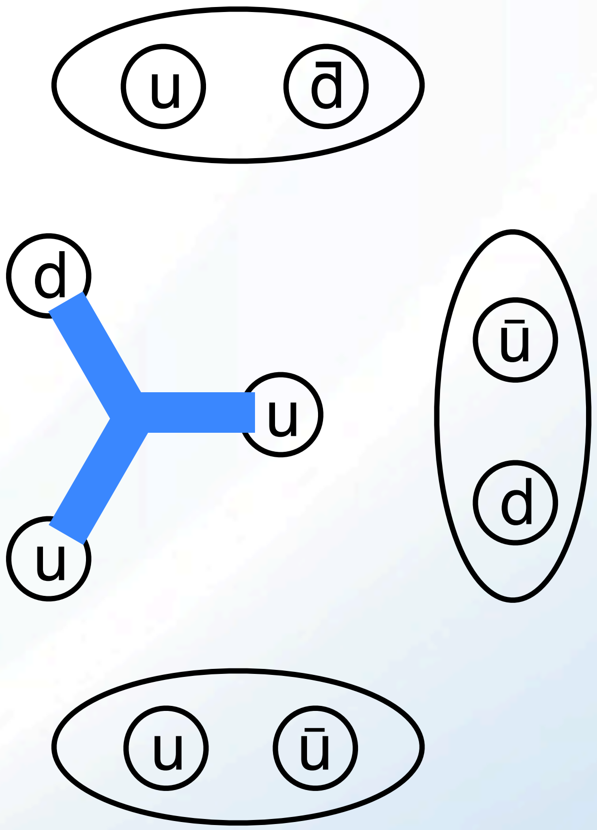


F. Bissey et al., PRD76, 114512

The “cloudy” proton



Fluctuating size and shape

The “stringy” proton

C. Coleman-Smith & BM, arXiv:1307.5911

Fluctuating size and shape

The “stringy” proton

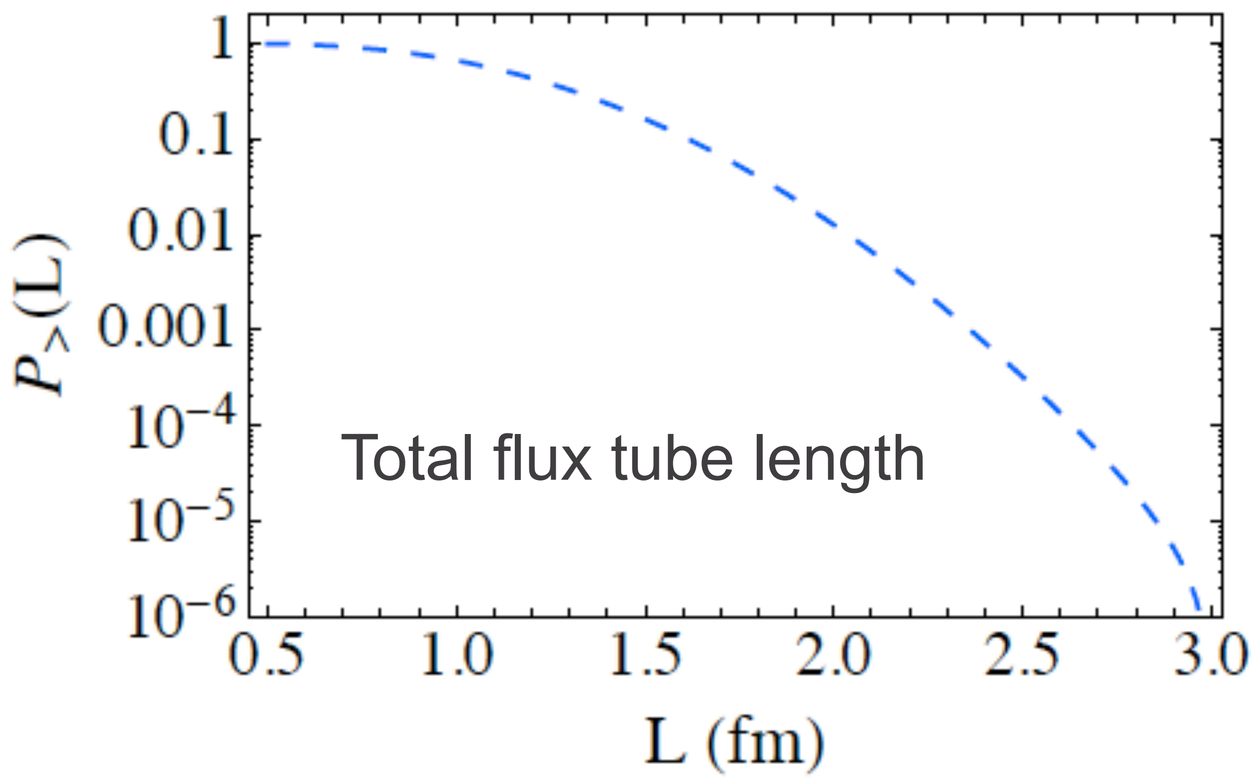
The “cloudy” proton

C. Coleman-Smith & BM, arXiv:1307.5911

Proton obesity is rare

The "stringy" proton

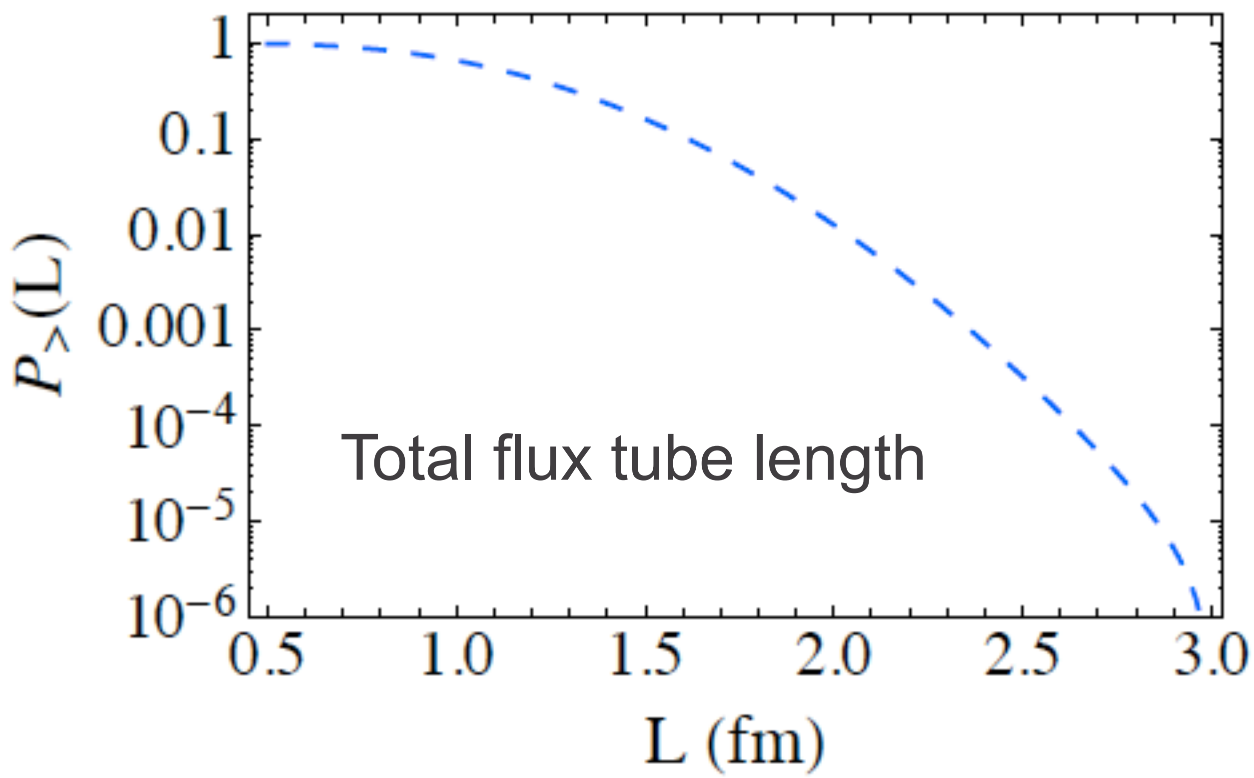
The "cloudy" proton



In both models, "fat" proton energy is shared among many more partons. Leading quarks have less energy; but there is a larger quark or gluon sea. Can this be used to differentiate the models?

Proton obesity is rare

The "stringy" proton



In both models, "fat" proton energy is shared among many more partons. Leading quarks have less energy; but there is a larger quark or gluon sea. Can this be used to differentiate the models?

The "cloudy" proton

P_N = probability for a proton to be accompanied by N virtual pions

N	P_N	$N_Q/3$
0	0.89	1
1	0.104	1.67
2	0.0062	2.33
3	2.4×10^{-4}	3
4	7.2×10^{-6}	3.67

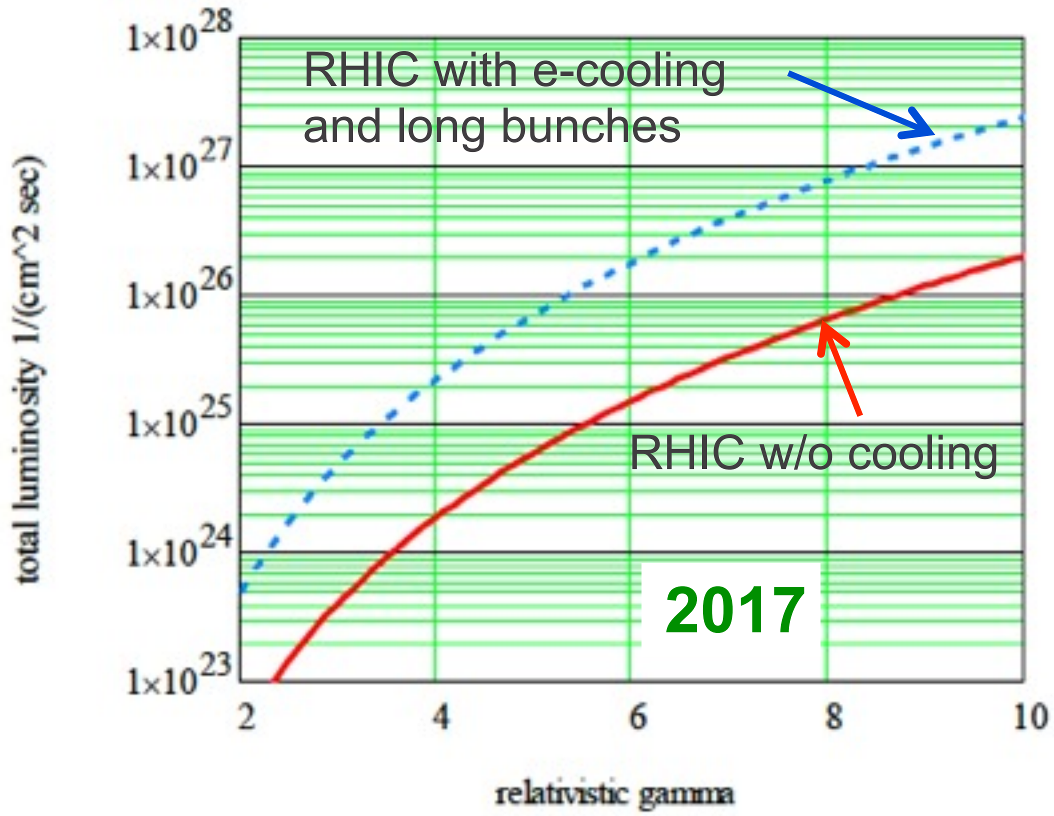
Future Plans

Planned Upgrades

Machine upgrade:

Bunched beam electron cooling for low-E beams

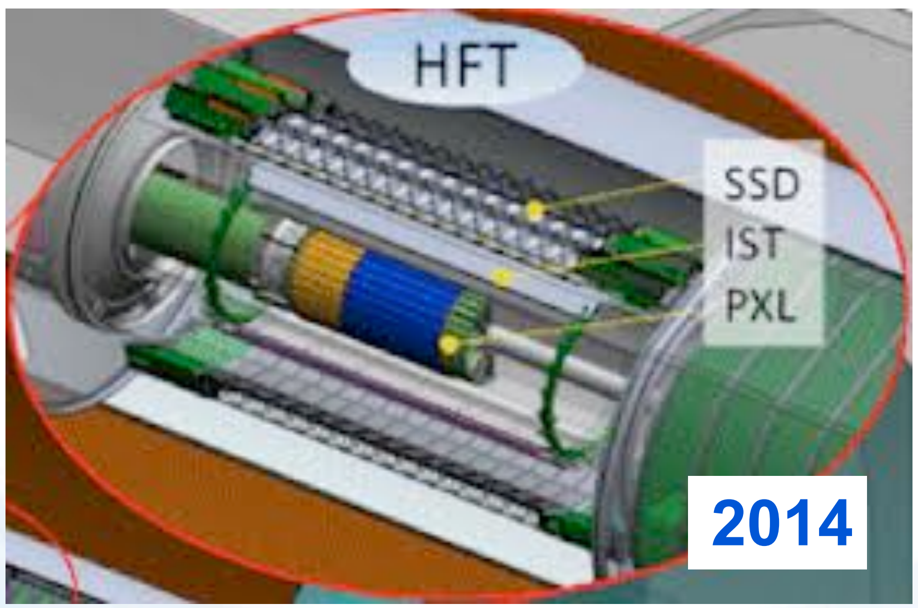
~10x luminosity



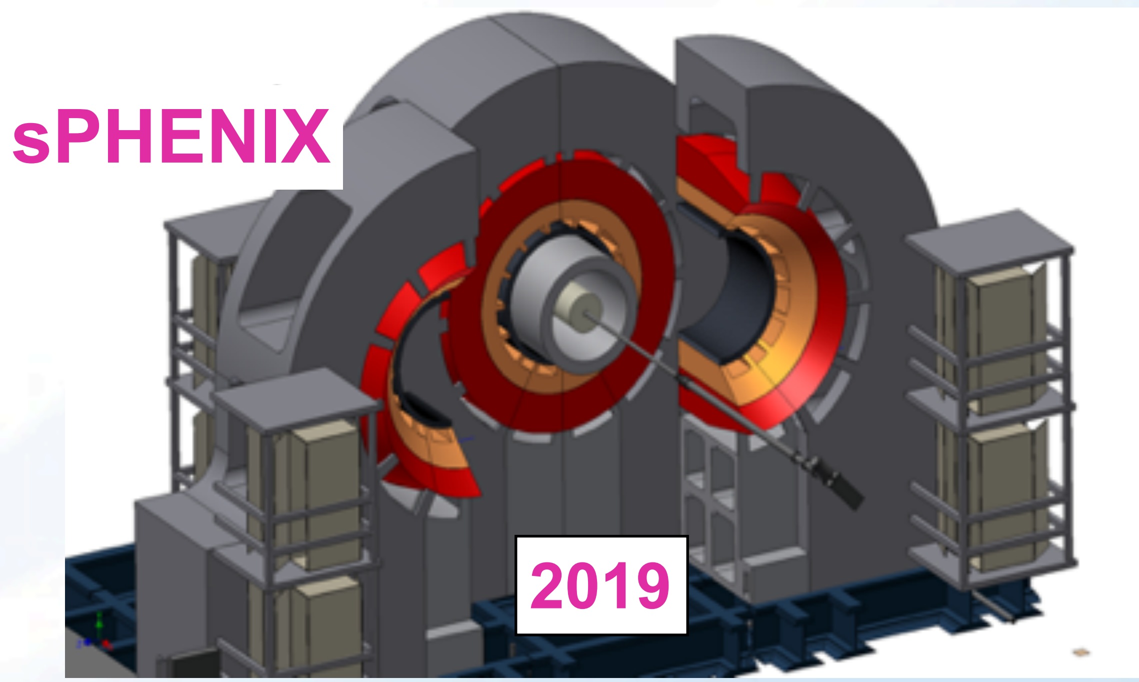
Detector upgrades:

- **STAR HFT**
- **PHENIX MPC-EX**
- **STAR TPC pad rows**

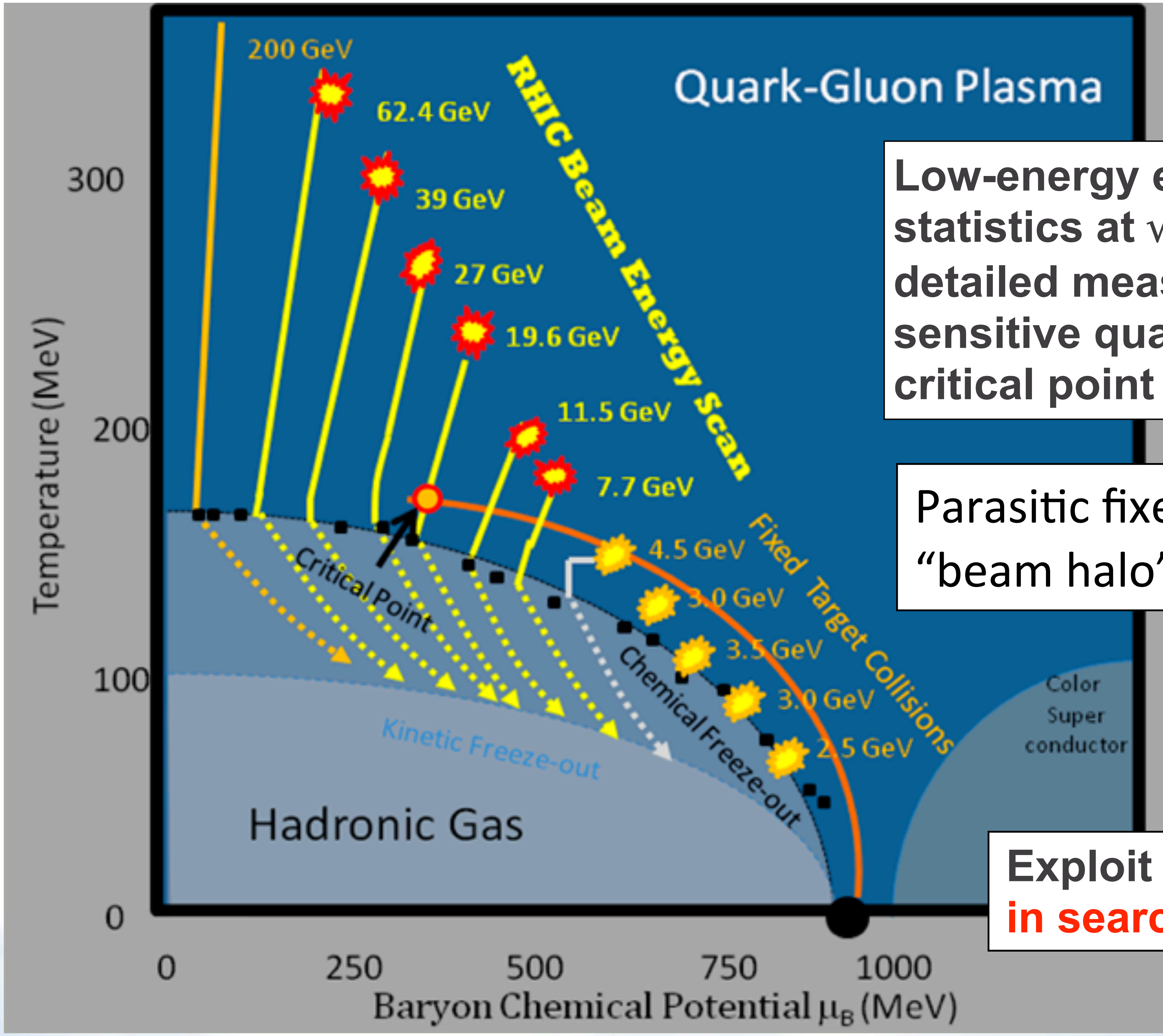
- **sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC**



STAR Heavy Flavor Tracker



Beam energy scan II



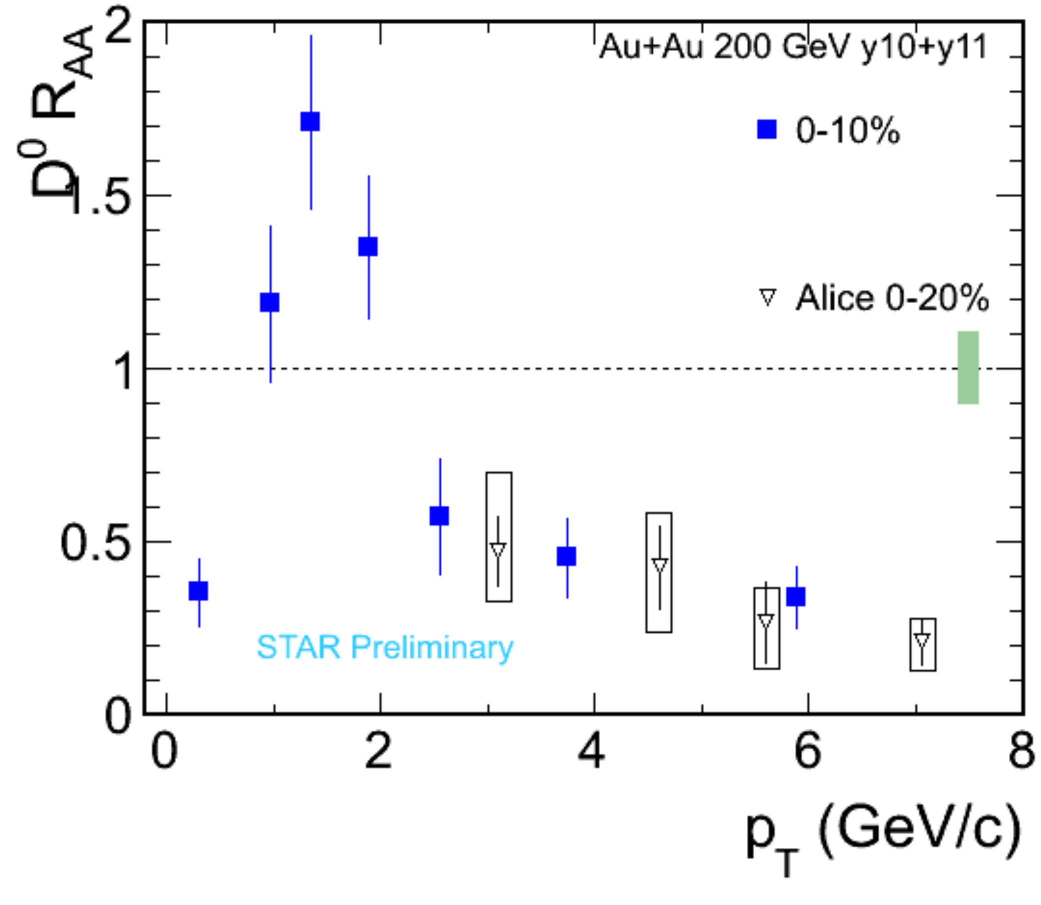
Low-energy e-cooling will improve statistics at $\sqrt{s}$ < 20 GeV for detailed measurements of sensitive quantities in search for critical point

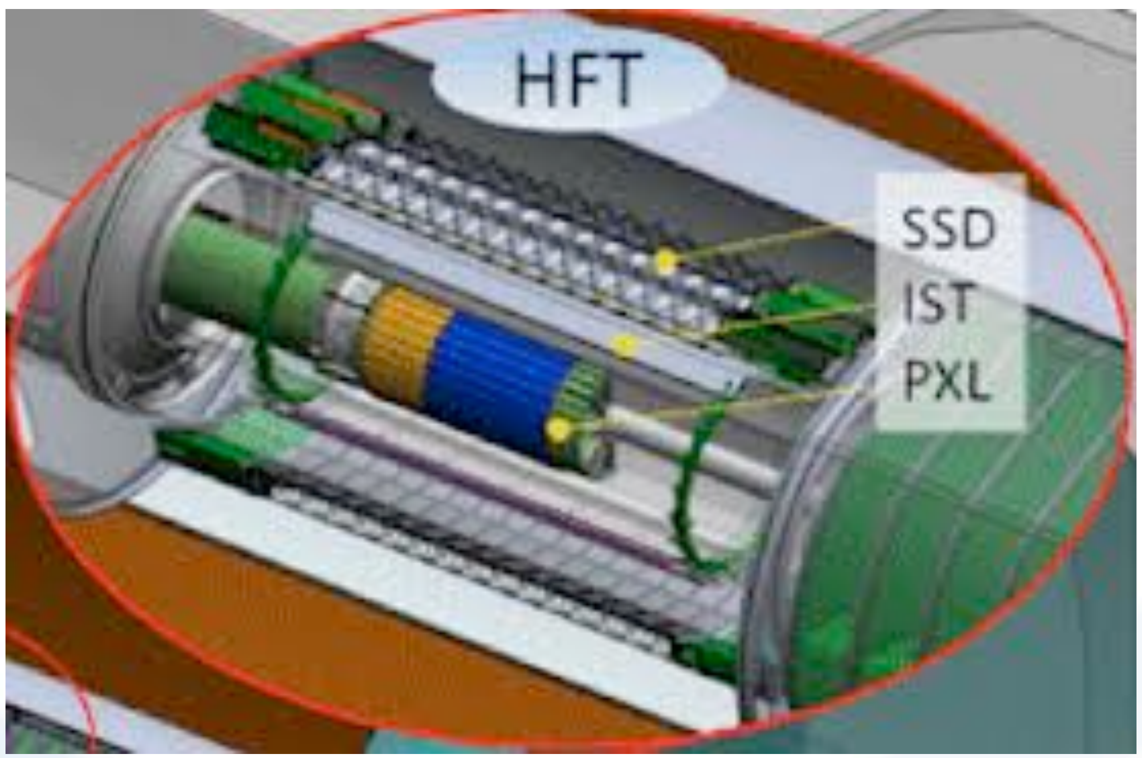
Parasitic fixed target mode by utilizing "beam halo" inside STAR detector

Exploit new discovery potential in search for a QCD critical point

Probing the sQGP with heavy quarks

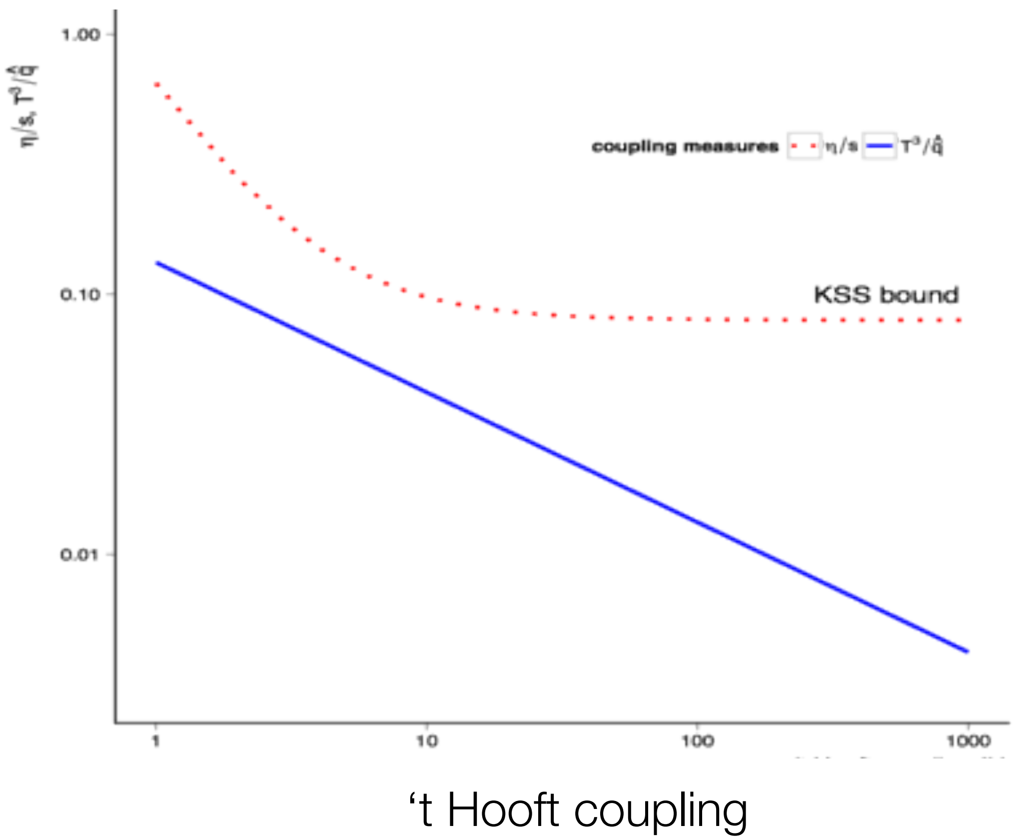
Quantify properties of the QGP by measuring heavy quarks and features of the QCD phase diagram as functions of temperature and net quark density.





Suppression of mesons carrying open heavy flavor = energy loss of heavy quarks (*c, b*) explores mechanism of energy loss via color response of the medium.

Providing Answers: Emergence of Strong Coupling

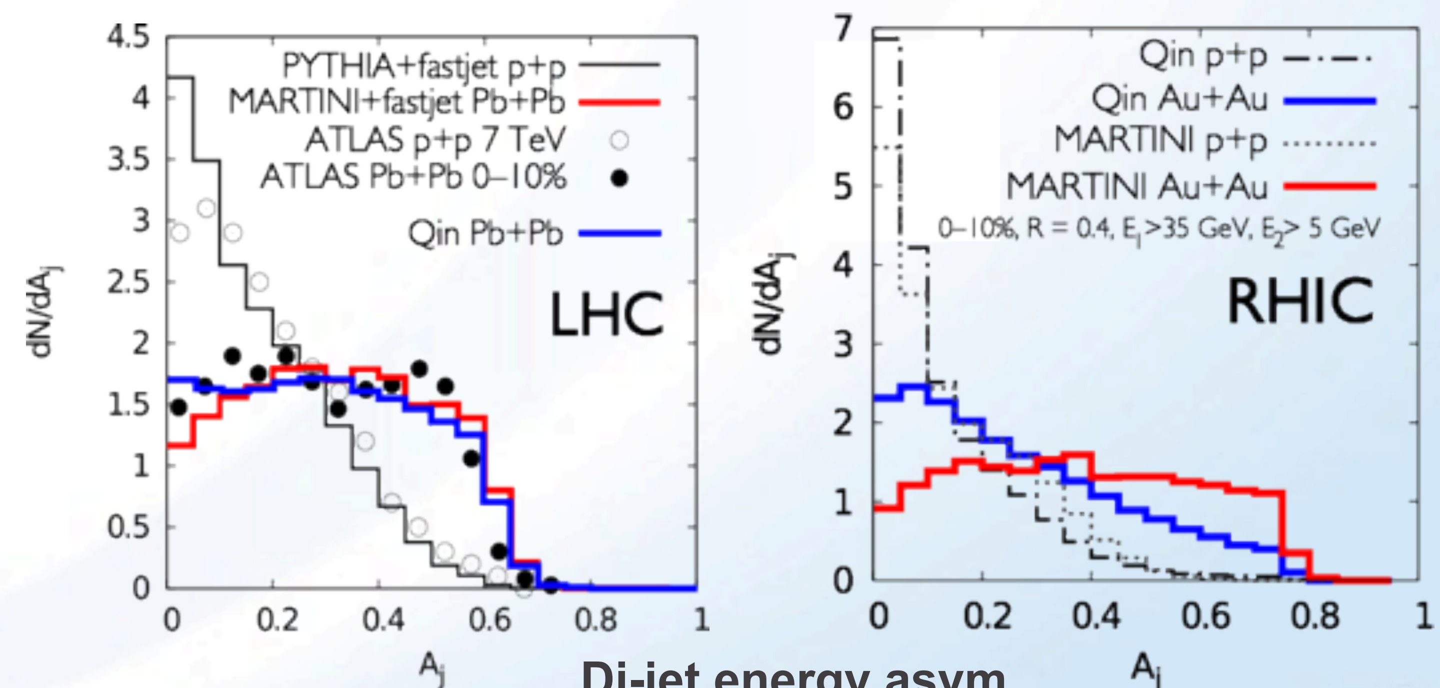


Low viscosity, rapid thermalization, and strong jet quenching are consequences of strong coupling

Determination of qhat(T), η/s(T) permits analysis of coupling strength

Requires measurements of jet, di-jet, γ-jet quenching, jet structure at multiple $\sqrt{s}$

sPHENIX upgrade will enable full jet reconstruction at RHIC



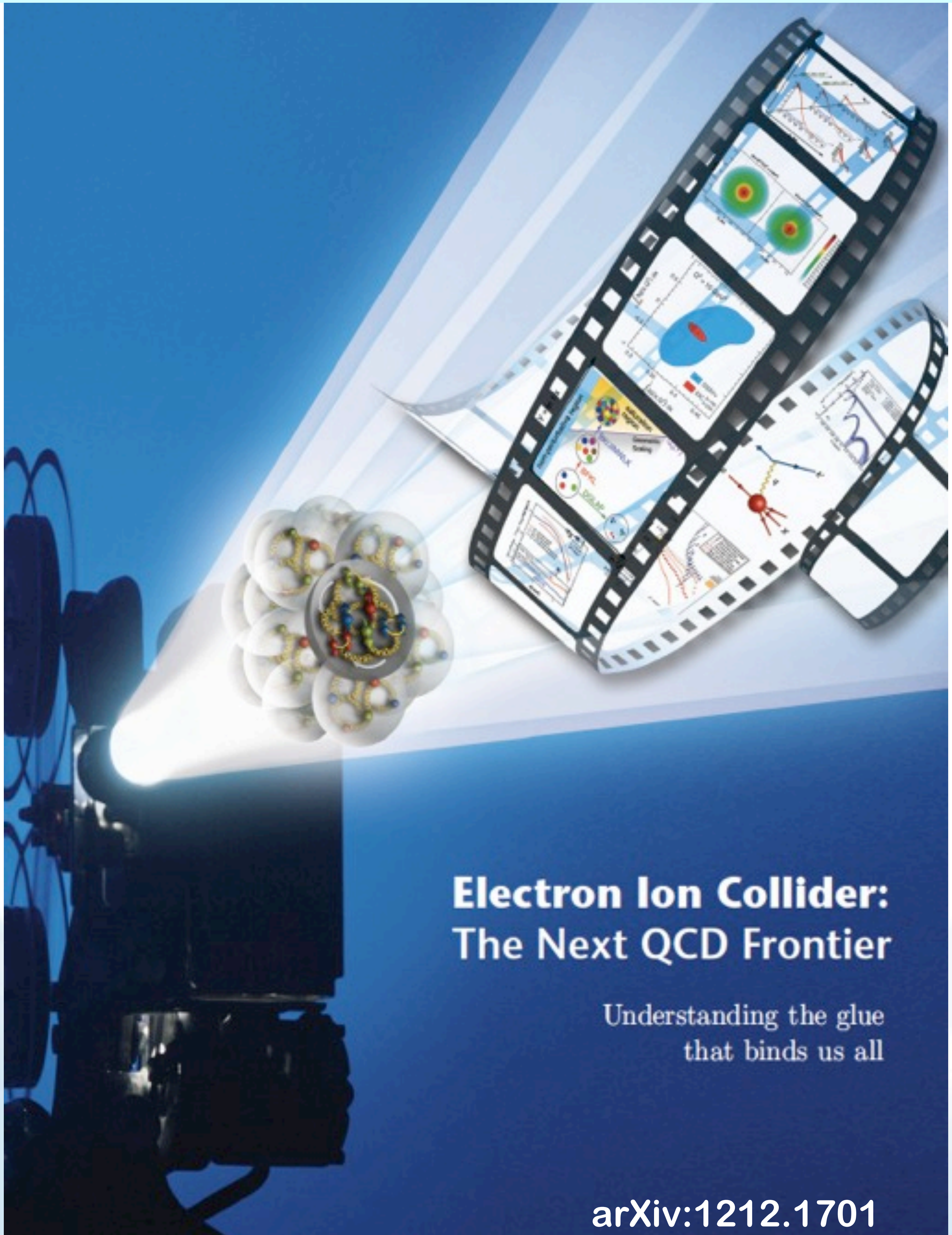
Di-jet energy asym.

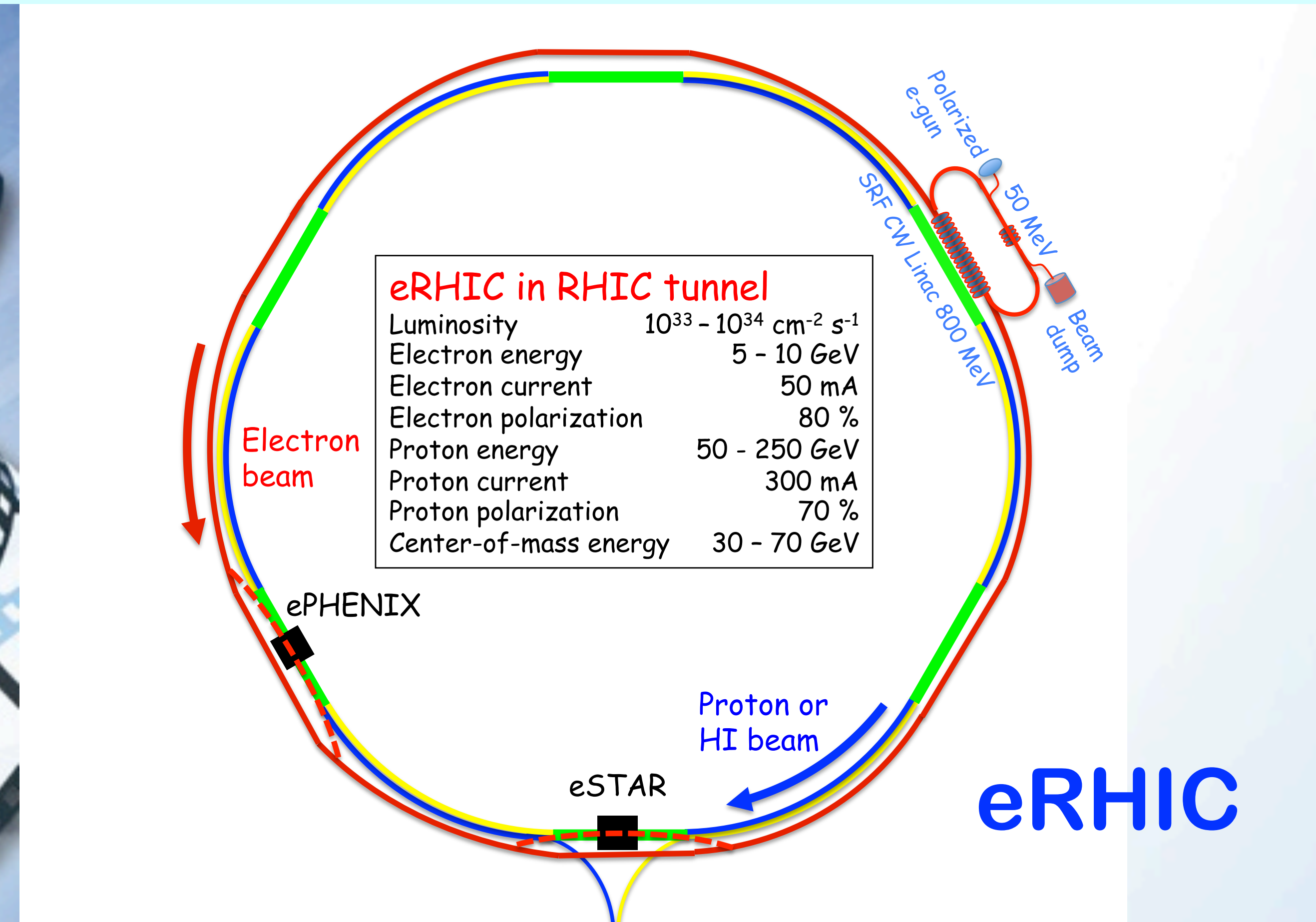
RHIC +LHC data can discriminate between models

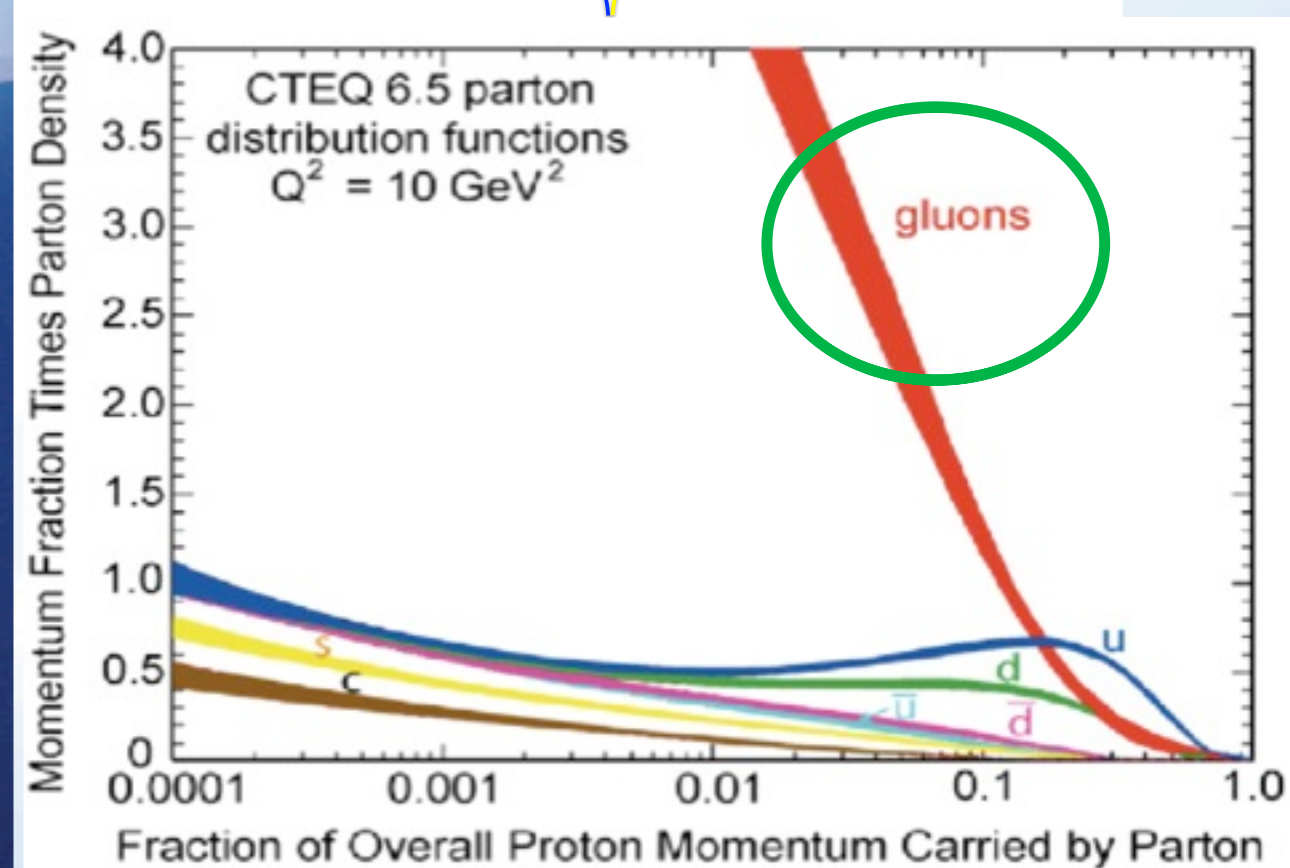
Run Schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 510 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	• Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		• sPHENIX installation
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p/d+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
2023-24	• No Runs		• Transition to eRHIC

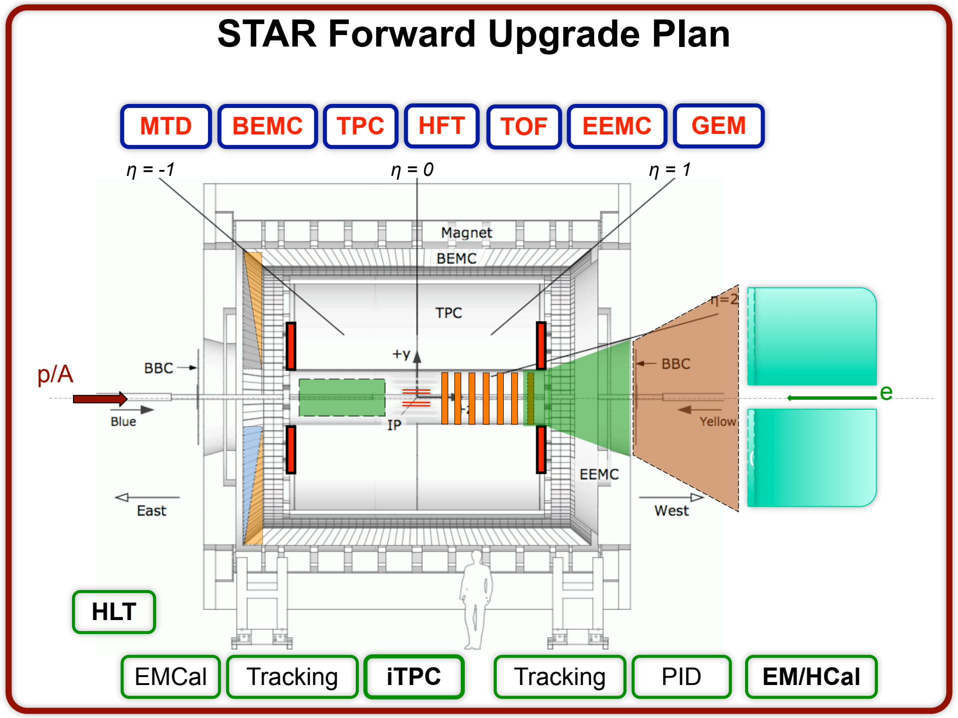
EIC: An electron microscope for QCD matter



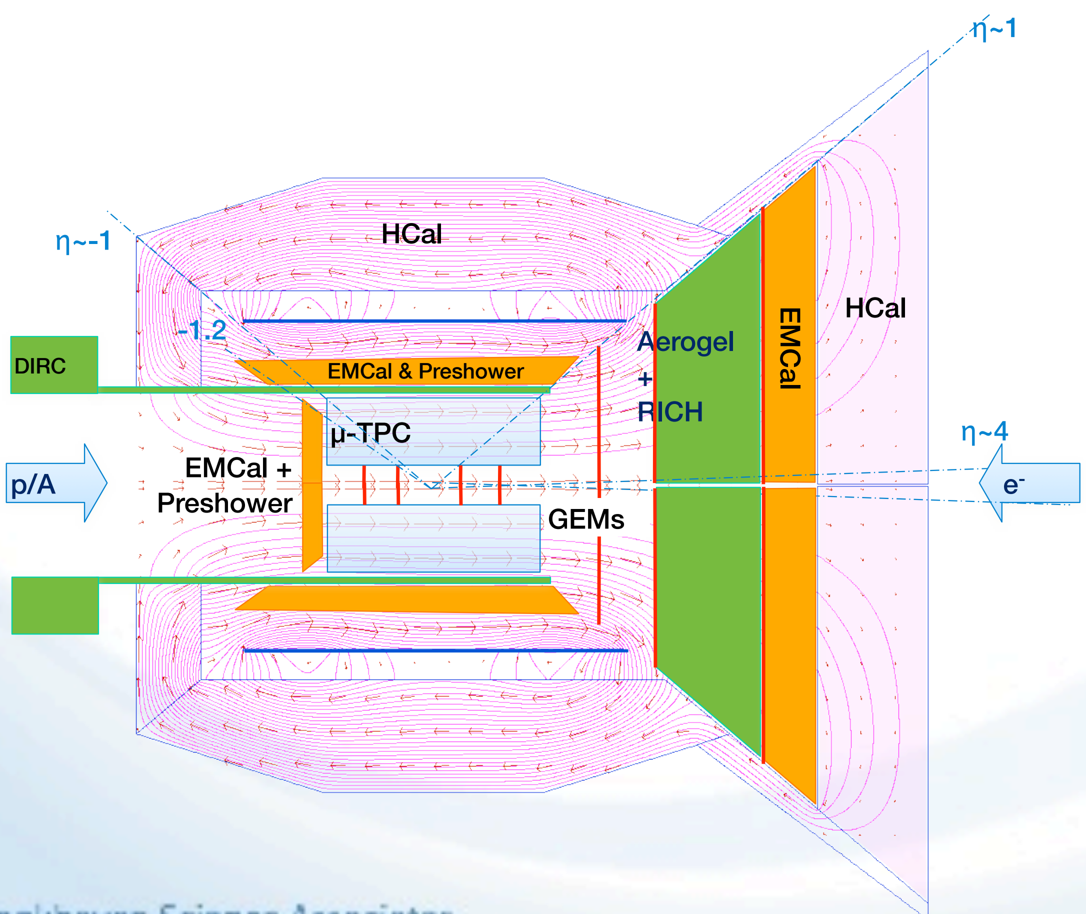


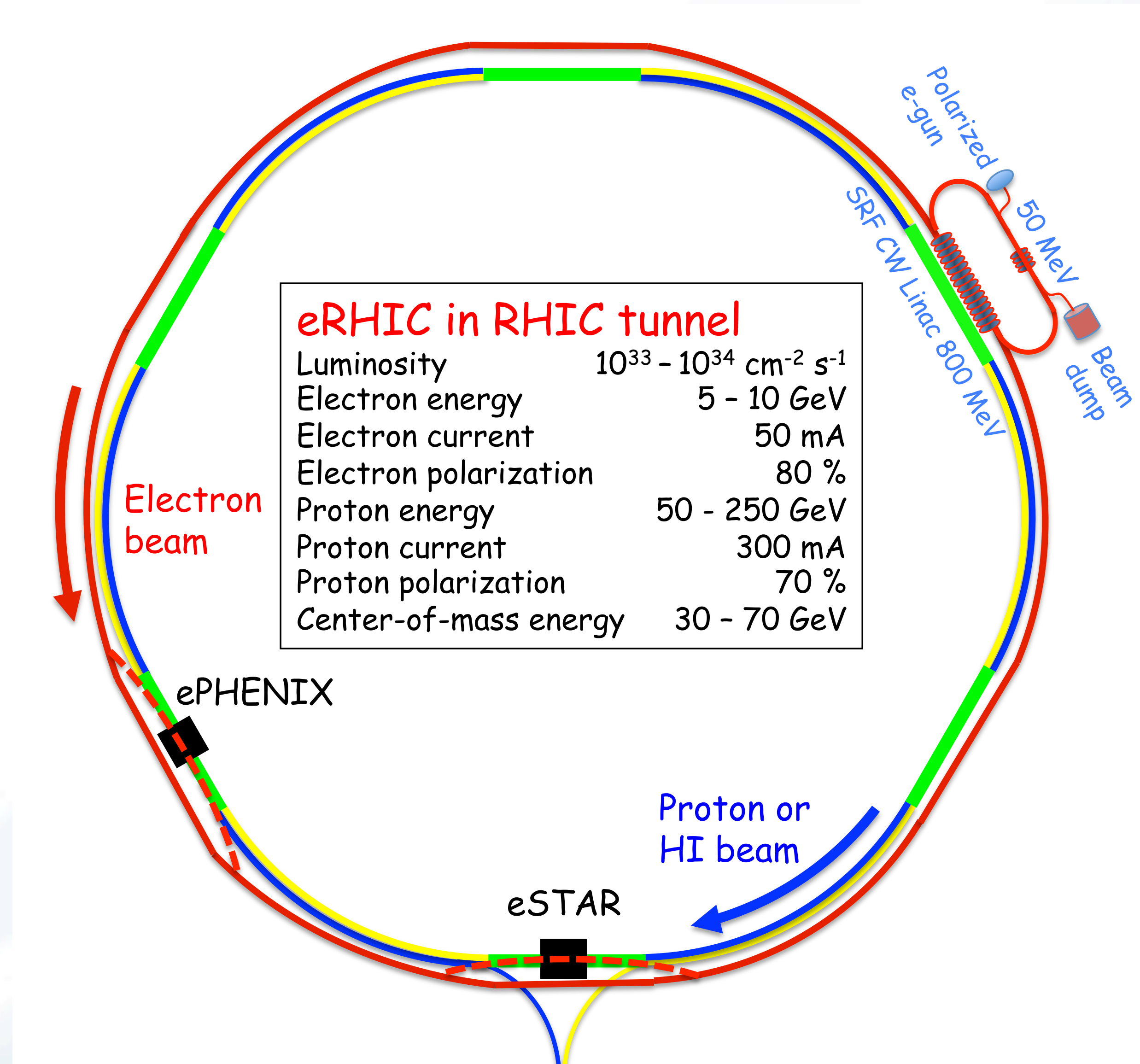


From RHIC to e-RHIC



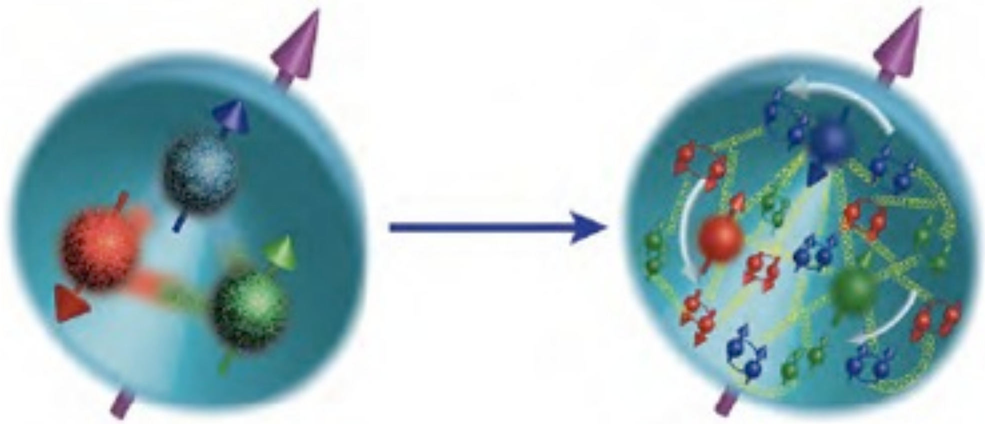
The 2013 NSAC *Subcommittee on Future Facilities* identified the physics program for an Electron-Ion Collider, as it was described in the 2013 EIC White Paper, as ***absolutely central*** to the U.S. nuclear science program in the next decade.



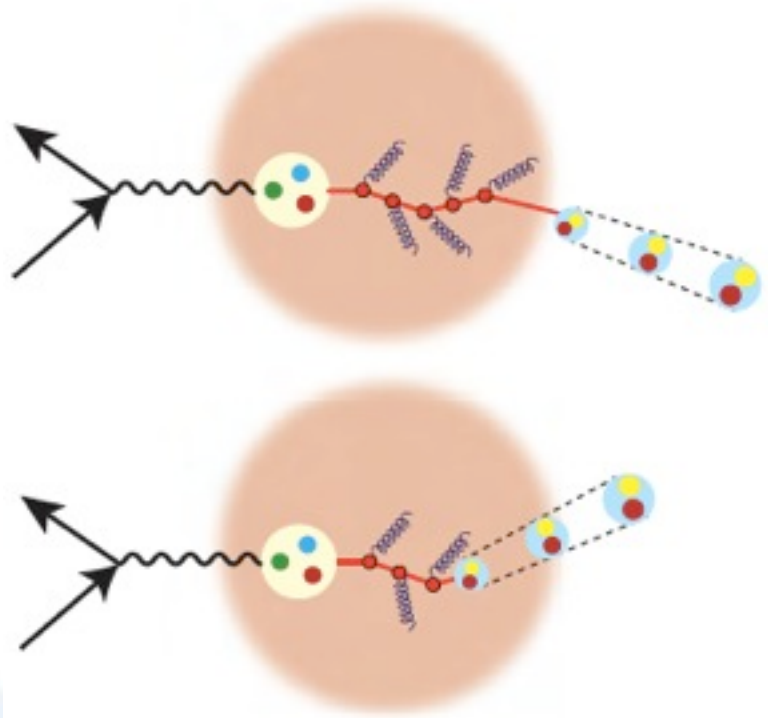


eRHIC will be a QCD laboratory

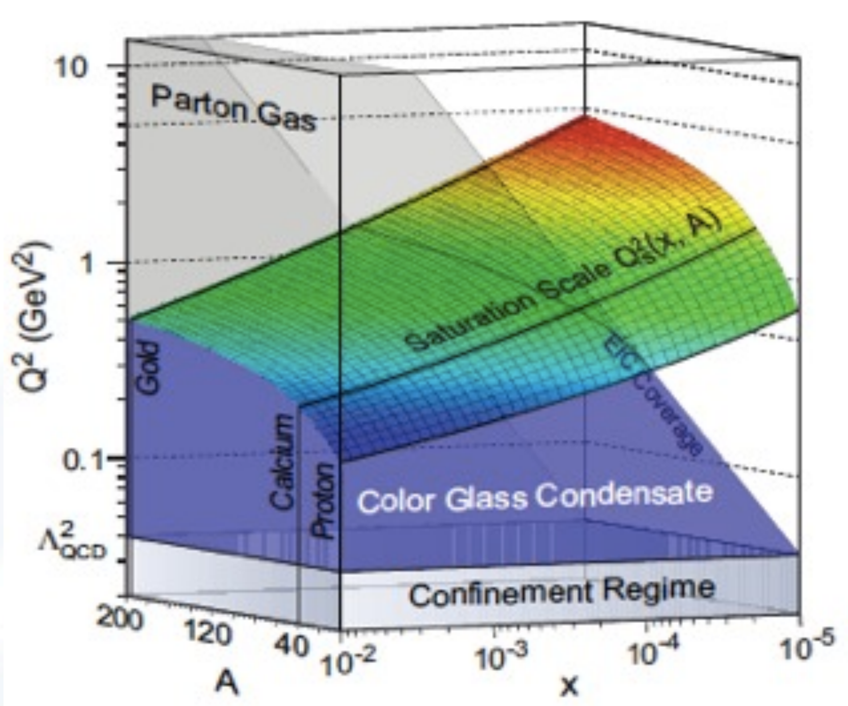
Gluon and sea quark structure of the proton



Using the nucleus as a fm-scale vertex detector to probe confinement



Is there a universal saturated gluon ocean (CGC) in nuclei?



Summary & Outlook

Insights and Questions

- **QGP at LHC is less strongly coupled than at RHIC**
  - Average η/s at LHC larger than at RHIC
  - QGP at LHC appears less opaque than at RHIC
- **Using E-by-E fluctuations as a versatile probe**
  - Can initial state structure and viscous effects be separated?
- **Jet physics opens new avenues of probing the QGP**
  - Matter effect on jet structure creates probes of scales
  - Kinematic threshold between quasiparticle and liquid domains ?
- **Quarkonium spectroscopy blossoms**
  - Quarkonium melting is more than static screening
  - Does recombination dominate at LHC for c-cbar states ?
- **Cold QCD matter**
  - Can QGP be formed in rare (?) p+A & d+A collisions?
  - An EIC is the QCD laboratory of the future